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FEASIBILITY OF RECTANGULAR CONCRETE PRESSURE VESSELS FOR HUMAN OCCUPANCY

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The technical and cost feasibility of post-tensioned concrete construction for large, multiplace, elevated pressure medical treatment facilities is established. A preliminary design of a rectangular shaped concrete pressure vessel is described. The chamber is designed for treatment of 18 patients at pressures up to 6 ATA. Other features of the proposed design include a large rectangular door and a unique slot window. Preliminary design is based upon American Concrete Institute (ACI) standards that are widely used by the construction industry. Detailed structural analysis is performed on the main components to demonstrate technical acceptability. The preliminary design is estimated to cost 1/4 that of a conventional facility constructed of steel. Risk factors that may increase cost are defined. Conventional strength concrete was found to offer the most economical design. The design and construction of a rectangular concrete HBO room can be done in accordance with Quality Assurance provisions established through the combined efforts of the ACI and the ASME Boiler and Pressure Vessel Code. The provisions of ASME Section III, Division 2, can and should be incorporated into the ASME PVHO-1 rules.

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ABSTRACT

The technical and cost feasibility of post-tensioned concrete construction for large multiplace elevated pressure medical treatment facilities is established. A preliminary design of a rectangular shaped concrete pressure vessel is described. The chamber is designed for treatment of 18 patients at pressures up to 6 ATA. Other features of the proposed design include a large rectangular door and a unique slot window. Preliminary design is based upon ACI (American Concrete Institute) standards that are widely used by the construction industry. Detailed structural analysis is performed on the main components to demonstrate technical acceptability.

The preliminary design is estimated to cost 1/4 that of a conventional facility constructed of steel. Risk factors that may increase cost are defined. Conventional strength concrete was found to offer the most economical design.

The design and construction of a rectangular concrete HBO room can be done in accordance with Quality Assurance provisions established through the combined efforts of the ACI and the ASME Boiler and Pressure Vessel Code. The provisions of ASME Section III, Division 2 can and should be incorporated into the ASME PVHO-1 rules.

BACKGROUND

The earliest application of hyperbaric medicine was during World War II for the treatment of decompression sickness in US Navy "frogmen". In the last 10 years hyperbaric oxygen (HBO) therapy has expanded beyond use by the military to public hospitals and clinics.

The origins of HBO therapy for uses other than decompression sickness can be traced to the pioneering work of the US Air Force. Early in the 1960's the USAF installed small US Navy aluminum chambers to treat aviators that experienced decompression sickness. In 1964 a large steel chamber was installed at the USAF School of Aerospace Medicine (SAM). The addition of this chamber facilitated the growth of the USAF SAM into the major USAF treatment center for hyperbaric therapy and the center for research on aviator decompression sickness. In recognition of the importance of the research and treatment performed by SAM, the USAF Hyperbaric Center at the USAF School of Aerospace Medicine was established in April, 1974.

The USAF SAM steel chamber is a horizontal cylinder. It is rated at 90 psig (7 ATA) and was fitted with 6 foot diameter circular doors. The original chamber was divided into two separate compartments that could be individually pressurized, a so-called "double lock". The outer lock had doors both to the inner lock and to the outside. The inner lock connected to the outer lock only. The need for additional usable space eventually led to the conversion of the chamber into a single lock unit. The 6 foot intermediate door proved a major annoyance and was removed.

The pressure vessels that have been used for medical HBO treatment are adaptations from US Navy and commercial diving deck decompression chambers (DDC). Commonly, DDCs are steel cylinders with the longitudinal axis laying horizontal. They are 6 foot to 8 foot in diameter and are portable, skid mounted and fitted with lifting brackets for ship board handling. They have small circular doors ranging from 22" to 30" diameter and small (4" to 6") round acrylic windows. Operational depths range from 300 to 1500 feet (20 - 100 ATA).

Safety certification of these DDCs and the associated personnel transfer capsules (PTC) provided the stimulus for the development of an industry specific set of rules for the design of pressure vessels for human occupancy (PVHO). Problems of concern to the diving industry included shipboard handling loads, selection of tough, fracture resistant steels and the design of transparent windows. Also of concern, was the design of the PTC which was exposed to external pressure.

The primary rules for the design of the DDC and PTC came from the ASME Boiler and Pressure Vessel Code, Section VIII (ref. 1). The ASME rules were widely accepted as conservatively safe but restrictive and in some cases incomplete. The diving community petitioned the ASME to form a special Standards group that would address the special problems of DDC and PTC vessels. The PVHO Committee was formed in 1974 and worked for 10 years to produce the ANSI Safety Standard for Pressure Vessels for Human Occupancy (ref. 2). The primary emphasis of the PVHO activity was the diving community both military and commercial; however, other organizations such as the Underseas Medical Society envisioned a wider application of PVHO rules.

The pressure vessel needs of the medical HBO are unique but not unlike those of the diving industry. Both groups needed rules for design and certification of acrylic windows, a topic that the ASME Boiler and Pressure Vessel Code steadfastly refused to consider. Both also shared concern for occupant safety and the need to prevent a sudden loss in pressure due to safety valve discharge. One topic that brought the HBO medical community into full involvement with the PVHO Committee was the use of monoplace chambers for medical treatment. The monoplace HBO chamber is an acrylic plastic tube just large enough for one person. These small portable units expose the occupant to 100% oxygen and in so doing pose a potential for fire. The monoplace chambers are economical, but they have significant limitations, particularly, when the occupant needs assistance (ref. 3). The PVHO Committee became involved when its design rules for submersible windows were applied to the acrylic plastic tube of monoplace chambers.

The special needs of commercial and military medical HBO treatment facilities dwarfed those of monoplace chambers and soon became a major extension of the scope of interest of the PVHO Committee. These medical HBO facilities which treat many patients simultaneously are installed in or adjacent to hospitals and clinics. Multiplace PVHOs are generally steel cylinders, usually horizontal, 84-96" diameter and pressure rated at 75-100 psig (6-7 ATA). All are double lock to allow patient or attendant exchange without depressurizing the main treatment chamber. Most are fitted with a rectangular door for patient egress. The door is about 3 feet wide by 6 feet tall. Commercial medical HBO chambers are fabricated by pressure vessel shops to the rules of PVHO-1 (ref. 2) and are truck transported to the HBO Treatment Center.

The US Air Force is the major sponsor of HBO hospital facilities. Since 1985, two major multi chamber HBO treatment facilities have been installed. The facility at Wright Patterson AFB, the WPCHF (Wright Patterson Clinical Hyperbaric Facility) has been in operation for about one year. The David Grant (DGCHF) complex at Travis AFB, CA. is due to commence operation soon. A third facility is planned for Portsmouth Naval Hospital.

All of the USAF facilities consist of three steel pressure vessels. The primary treatment is done in a 20 to 23 foot diameter sphere or upright cylinder. Emergency treatment and overflow is assigned to an adjacent upright (longitudinal axis vertical) cylinder varying in size from 11 foot diameter on the first installation at WPCHF to a 14 foot diameter for the most recent facility. A third upright cylinder acts as the lock to the other chambers. The locks vary in size from 11 to 12 foot diameter. The three chambers are interconnected with rectangular passageways. The doors to the outside and at either end of the passageways are rectangular with a clear opening of 3 feet by 6 feet. All windows are circular with the maximum size being 15" diameter.

The primary or main treatment chamber of the USAF facilities is constructed at the hospital site. The other smaller chambers are built in pressure vessel shops and transported by rail or truck. Final assembly consists of field welding the rectangular passageways to the chambers.

Virtually all of the multiplace medical PVHOs have been built from steel using conventional pressure vessel fabrication technology. The exceptions are few, two place acrylic and steel and all stainless steel PVHOs and some converted aluminum diving recompression chambers. Other materials have been suggested; fiberglass composites for collapsible and portable applications and prestressed concrete for the large hospital installations.

PRESTRESSED CONCRETE PRESSURE VESSELS

Prestressed concrete has a history of being used for pressure vessels. Concrete is a preferred construction material because of its low cost, but concrete has a major limitation when applied to pressure vessels. Concrete is strong in compression but exceedingly weak when pulled in tension. An inherent requirement of a structure to contain pressure is its ability to resist the tensile loads of an expansive pressure.

The combination of concrete and steel wire in prestressed concrete is an excellent matching of the complementary strengths of two materials to overcome the other material's limitations. The steel wires have the opposite characteristic to concrete. Steel wires are good in tension but buckle when compressed. Prestressed concrete combines concrete and steel in such a way as to precompress the concrete and pretension the steel. Tensile cracking of the concrete is inhibited and the steel wires are pre-elongated. The initial prestressing must be sufficient to produce a resultant compressive preload in the concrete after time dependent effects of creep in the concrete and relaxation in the wires occur.

Prestressed concrete is suitable for large field fabricated structures. Perhaps its earliest application in pressure vessels was in agricultural silos. In the 1930's, concrete silos were circumferentially prestressed to resist the internal pressure of grain and silage. Bridge and skyscraper applications of prestressed concrete followed thereafter. Today prestressed concrete is widely used in civil engineering structures throughout the world.

A major development of prestressed concrete for pressure vessels initiated in Europe in the 1960's. Europe's need for energy led to the development of PCRV's (Prestressed Concrete nuclear Reactor Vessels). Prestressed concrete was used for the construction of more than 20 gas cooled nuclear reactors that operated at pressures from 350 to 700 psig. These were massive pressure vessels ranging in size from 50 foot diameter up to more than 100 feet. All used circular prestressing to resist the tensile hoop stresses and a combination of linear and curved tendons carried the end loads. Gas cooled reactors were never very popular in the US. Domestic utilities preferred boiling water reactors that operated at pressures in excess of 2500 psig. In the 1960's, concrete strength was insufficient to contain these higher pressures.

One gas cooled prestressed concrete reactor was built in the US at Fort Saint Vrain, Colorado. It was an upright cylinder 75 feet high with an internal cylindrical cavity diameter of 31 feet. Six vertical buttresses, which provided tendon anchorage sites, increased the wall thickness from a nominal 9 feet to 15 feet. The top and bottom slabs were 15-1/2 feet thick. The PCRV was prestressed using 600 ton tendons. The circumferential or hoop prestress was generated by linear tendons deformed into a half loop and anchored at the buttresses. The end load was transferred from arched tendons in the end to vertical tendons in the cylinder through the concrete. The Fort St. Vrain PCRV weighed 15,000 tons and contained 6600 cu.yd. of 6,000 psi concrete. This reactor, the only PCRV built in the US, has been closed.

In anticipation of other gas cooled reactors being built in the US and to satisfy the Nuclear Regulatory Commission's Quality Assurance Standards for the concrete nuclear containment structures, the nuclear subcommittee of the ASME Boiler and Pressure Vessel Code initiated development of a special Division dealing with concrete. In 1971, the ASME began a joint effort with the American Concrete Institute (ACI). The rules governing concrete for nuclear reactor pressure vessels were first published in 1976 as Section III, Division 2 (ref. 4).

Also in the early 1970's, the US Navy was developing a deep ocean capability. The DSRV (Deep Submergence Rescue Vehicle) and the DSSV (Search Vehicle) were seen as vanguards of a new class of deep submergence hardware. Testing of this hardware was a necessity. Failures at sea were costly and the remnants often unrecoverable. Deep ocean simulators were available at many Navy Labs, but even the newly commissioned 12 foot diameter, 20,000 psi test vessel built at the Annapolis Naval Ship Research and Development Laboratory was thought to be too small. A major study was initiated in 1971 to investigate alternative design concepts for large high pressure vessels.

The study (ref. 5), examined construction methods for chambers of two extreme sizes and pressure ratings. The smaller chamber was a 20 foot diameter by 60 foot long, 30,000 psi chamber for component testing. The second was to be a 75 foot diameter, 600 foot long, 4000 psi pressurized facility for proof testing of full scale combat submarines. Concrete was found to be the most feasible construction method for the large tank. The study established the primary technological risk as development of high strength concrete. The 4000 psig design pressure was achievable only at concrete compressive strengths of 14,000 psi. At the time of the study, commercial concrete strengths of 5000 to 6000 psi was considered good practice.

In the late 1970's, interest in large concrete chambers as alternatives to steel PVHOs revived. NAVFAC (Naval Facilities Engineering Command) sponsored a cost comparison study (ref. 6) of two chambers; one a 15 foot diameter, 1000 psi PVHO and the second a 10 foot diameter, 20,000 psi research and hardware test vessel. The proposed concepts used conventional circular prestressing of concrete. The cost comparison showed a 70% cost savings for the manned 1000 psi tank over conventional steel.

The issue of concrete for pressure vessels was also of interest to the Department of Energy in the mid 1970's. One solution proposed for the oil shortage was coal gasification. An ACI Committee was formed to develop standards for large pressurized concrete cylinders for coal gasification plants. Large high pressure, high temperature retorts were needed to convert coal into gasolene. Pressures of 3000 psi on diameters comparable to PCRV's required walls of high strength concrete 10 to 30 feet thick. Concrete was found to be an economical alternative to steel. Savings were estimated to be 70% (ref. 7).

During the 1980s, the oil crisis became a glut and interest in coal gasification disappeared. The ACI group sought other applications where concrete was cheaper than steel. Potential uses were offshore storage tanks and hydrocracking vessels and vacuum stills in oil refineries. In 1988 the group became dormant for want of a specific application that needed a concrete solution.

The USAF also was conducting cost studies of HBO chambers in the late 1970's. A cost tradeoff investigation compared horizontal and vertical cylinders and rectangular concrete rooms (ref. 8). The operational scenario used two interconnected 6 ATA chambers. The larger chamber accommodated 10 patients and 2 medical attendants and would be used for scheduled HBO therapy. A second smaller chamber, for emergency treatment, was sized for 2 patients with 2 attendants.

Options for the main treatment chamber were:

1.) a 12' diameter by 25' long horizontal steel cylinder,

2.) a 19' diameter vertical cylinder, or

3.) a 10' wide, 25' long by 8'high rectangular concrete room.

The emergency treatment chamber alternatives were:

1.) a 12' diameter by 10' long horizontal steel cylinder, 2.) a 12' diameter vertical cylinder, or

3.) a 10' square by 8' high rectangular concrete room.

Preliminary cost estimates showed the cost of the steel chambers to be in the $125,000 to $169,000 range. The concrete chambers showed a 30% to 40% cost savings.

In 1984, the option of vertical versus horizontal cylinders was examined in more detail (ref. 9). This study provided the basis for size and configuration of Wright Patterson Clinical Hyperbaric Facility (WPCHF). A vertical cylinder was selected over horizontal for two reasons: (1) it gave the maximum floor space for chamber volume and (2) it reduced interference in patient movement.

This investigation also showed that the number of patients that can be treated is directly proportional to floor area. The study developed a rational for assuming that 36 ambulatory or 20 litter patients would be treated per day. Further, experience had shown that 2 pressurizations (dives) could be made in one work shift. Accordingly to minimize the number of operational shifts, the ideal capacity of the main chamber was 18 ambulatory patients. This translated into a 22 foot diameter upright cylinder.

It was also shown that a smaller 14 foot chamber had a lesser first cost but the additional operational expenses of running a second shift canceled the first cost differential in 9 years. The main treatment chamber in the WPCHF is a 22 foot upright cylinder.

HIGH STRENGTH CONCRETE

Many studies have shown that high strength concrete is either desirable or mandatory for concrete pressure vessels. In the last few years higher strength concrete has gained wide attention. It is used increasingly in high rise buildings where its greater elastic modulus (stiffness) reduces building sway. As building height increases, motion at the upper floors becomes the design constraint. The high strength which is specified for stiffness in the building columns also reduces column size and thereby increases the leaseable floor area. This combination of increased stiffness and more floor area has led to pioneering advances in commercial concrete strength.

The evolution in concrete strength reads as follows:

1968 - 7,500 psi in Chicago (Lake Point Tower);

1975 - 9,000 psi in Chicago (Water Tower Place);

1984 - 10,000 psi in Seattle (Century Square Bldg.);

1987 - 10,000 psi in Toronto (Scotia Plaza), 10,000 psi was specified but tests showed 13,000 psi was achieved;

1988 - 12,000 psi in Chicago (Prudential Plaza);

1988 - 12,000 psi in Atlanta (Portman Properties), 12,000 psi offered $5/sq.ft. savings over steel on a 1.4 million sq.ft. building;

1988 - 12,000 psi in Chicago (South Wacker Tower), 12,000 psi was used for reasons of economy although 14,000 psi was considered. At 946 feet South Wacker Tower is world's tallest concrete building;

1988 - 19,000 psi in Seattle (Two Union Square), 19,000 psi is the current record for high strength concrete.

The 19,000 psi concrete used in Seattle was initially specified as 14,000 psi with an extremely high elastic modulus of 7,200,000 psi. For comparison, conventional 6,000 psi concrete exhibits an elastic modulus of 4,700,000 psi. The high elastic modulus dictated the 19,000 psi concrete strength. Many of the concrete test specimens failed at > 21,000 psi.

This very high compressive strength concrete was achieved in a commercial batch plant through an extraordinary quality assurance (QA) program. The mix design specified an extremely low water to cement ratio of 0.22 (conventional concrete is 0.45). In addition, a very high cement content and strong, small (3/8") glacial aggregate was used. Silica fume, a very strong and fine aggregate filler was also a key ingredient. To work this stiff mix a superplasticizer was added.

Predictions are now being made of 25,000 to 40,000 psi concrete in the 1990s (ref. 10).

High strength concrete poses some new problems. Testing limits are being approached and conventional design rules are being questioned. Most test labs are equipped to evaluate < 6,000 psi concrete. Typically, they have a 300,000 lb. test machine which is adequate for destructively testing a standard 6" diameter by 12" long test cylinder. Testing of 20,000 to 30,000 psi concrete will require as much as a million pound test machine. Adding further to the cost of testing is the substitution of lapped ends on the test cylinder for the end capping compound that fails at 14,000 psi.

Of greater concern than testing costs is the potential discrepancy introduced by high strength concrete on the ACI Building Code (ref. 10). The ACI (American Concrete Institute) Code is used for buildings and other civil engineering structures. It is adopted throughout the US by local building codes as the regulatory guide for concrete construction. The ACI Code, like the ASME Boiler and Pressure Vessel Code, develops minimum requirements for safety. The basis of the ACI rules is experimental data on low to medium strength concrete. The ACI committee members have expressed concern that use of high strength concrete is spreading faster than knowledge of its engineering properties. The actual use of high strength concrete in other than high rise buildings has been quite small, but is growing.

To address these doubts the Portland Cement Association funded research on beams made from 17,000 psi concrete. The initial research findings supported only a minor change to current ACI rules for design with high strength concrete. Additional requirements for shear reinforcement have been proposed for local regions at stirrups and ties. More confirmatory studies are underway, but at this time the current rules appear to be adequate for concrete strengths up to 10,000 psi

NEED FOR PRESTRESSED CONCRETE PVHO

Why is there interest in concrete for PVHO's?

A defined need exists for additional multiplace treatment facilities. The USAF has requirements for additional medical PVHOs. It has been proposed that each military hospital district offer HBO treatment. At present in the ten hospital districts two have HBO facilities and a third has one in the design stage.

The cost of these facilities is appreciable. The steel vessel cost is on the order of $1-1/2 million. Cost reductions are desired. Prestressed concrete is seen as a source of cost savings. Previous studies, mentioned above, report cost savings ranging from a low of 30% for low pressure vessels to as much as 70% at higher pressures.

Another significant factor affecting new construction of multiplace PVHOs is the reality that far fewer domestic pressure vessel manufacturers are in business today than five years ago. Many of the PVHO vessel fabricators simply abandoned the business. Many were steel fabricators that served the diving industry. As the demand for oil fell commercial diving almost disappeared and so did these builders. They found it difficult to support high technology staffs when relatively few systems were being built. Also, major projects were frequently awarded to the lowest bidder rather than the most technically capable.

A significant feature of concrete PVHOs is the potential for design of rectangular rooms. Steel pressure vessels are cylindrical or spherical; a rectangular vessel is an anomaly. The ASME Boiler and Pressure Vessel Code, Section VIII, (ref. 1), devotes major sections to the design of curved pressure vessels. While rules for rectangular vessels are provided in an Appendix, the rectangular vessel is considered a special shape. Experience with the rectangular passageways used in the WPCHF and DGCHF clearly established that even for small rectangular vessels, (3 foot wide by 6 foot high) the ASME requirements produce extremely thick and expensive sections. The prospect of a steel rectangular vessel of a size comparable to the 23 foot main treatment chamber of DGCHF is low, because of high technical risk and high cost.

The advantages of rectangular rooms are many.

1. Rectangular treatment rooms give better space utilization. A conventional flat wall yields more usable floor space for litters and wall space for equipment and windows. Less gas volume is needed since the wasted volume in the curved heads of a conventional steel tank are eliminated. With a rectangular room the HBO facility requires less hospital space. It can be located on one floor whereas current facilities require a separate hospital addition.

2. Rectangular rooms are believed to be more acceptable to patients and hospital staff than the "Space Ship" appearance of steel chambers. A rectangular treatment chamber will appear similar to other hospital facilities.

3. Rectangular chambers facilitate the use of larger doors. The curved walls of steel PVHOs restrict the location of the massive doors and encroach on usable chamber floor area. Current practice is to design the door to swing on hinges, a sliding door is feasible in a rectangular chamber.

4. Larger and rectangular shaped windows are feasible in rectangular PVHOs. Circular windows are commonly used today. This geometry is in part a historical consequence of their use in cylindrical pressure vessels. Circular windows can be traced to round

piping penetrations in steel pressure vessels. Rectangular vessels with flat walls facilitate the specification of a rectangular or slot shaped windows. A slot shaped window offers improved visibility into a large chamber.

5. Laminar gas flow across the HBO chamber is difficult to achieve in a sphere or vertical cylinder but can be readily produced in a rectangular room. Laminar flow requires less recharge gas flow to eliminate carbon dioxide and odors. It also offers more uniform and predictable temperature control.

6. A rectangular concrete room adapts to conventional building architecture and can be constructed by the hospital building contractor. The advantages in dealing with one contractor are many. First, the interface to a specialty steel PVHO fabricator and its attendant scheduling problems are eliminated. A single contractor will be in a better position to control and thereby reduce costs and schedule.

Concrete for PVHOs is not without shortcomings. As a new material for HBOs acceptance may be slow. No rectangular concrete PVHOs have been built and accordingly some difficulties may lie hidden. It is not certain that the available codes are applicable. Should ACI or ASME be used? Will cities and states accept concrete PVHOs?

Technical issues need to be examined. Does outgassing and contamination from microfissures in the concrete pose a potential health hazard? Is a liner required? Is the concrete inspectable? Will high strength state-of-the-art concrete be required? The structural details may be formidable in a rectangular vessel. Cylinders are used for pressure vessels because pressure is best resisted by a curved geometry. Rectangular vessels have sharp corners, a feature that raises stresses and is avoided in conventional pressure vessel design. Local reinforcement at doors, windows and penetrations also needs to be examined.

In summary, concrete pressure vessels have a mixed history. A number of studies have shown cost advantages but few have been built to validate the studies. Recent technical advances in concrete strength suggest that this mundane material may be suitable for the high quality requirements of Pressure Vessels for Human Occupancy.

SCOPE OF STUDY

The objective of this study was to determine the technical feasibility of a rectangular concrete pressure vessel for medical PVHOs.

The scope of the study began with a review of the literature to establish current practice in concrete pressure vessels. Using state of the art knowledge, a preliminary design of a rectangular concrete pressure vessel was to be developed. Considerations of chamber size and shape and the special needs of medical PVHOs were to be addressed.

A preliminary structural analysis was to be performed to prove technical feasibility. The structural analysis was to include the main treatment chamber, the rectangular or slot window concept and a large rectangular door with a large circular window.

An order of magnitude cost for the rectangular concrete vessel was to be calculated and a cost comparison made to an equivalent steel vessel.

An evaluation of available Codes for applicability to concrete PVHOs was also included in the scope of the study.

APPROACH

The approach taken to determine the suitability of a rectangular concrete PVHO first established chamber size requirements to meet anticipated patient loads. Candidate designs were conceived to satisfy these size requirements. The technical acceptability of the candidate design was evaluated using conventional concrete design methods. Design confirmation of the candidate design followed. Detailed stress analysis was used to confirm structural adequacy.

The cost of the candidate design was estimated and compared to historical cost data for steel PVHOs. If cost savings were not found, the candidate design was revised and the design process repeated. Candidate designs were iterated until an acceptable technical and cost design was found.

Finally, an evaluation was made of the available Codes for applicability to rectangular concrete PVHOs.

CHAMBER SIZE AND GEOMETRY

The determination of the size and shape of a medical HBO treatment chamber is derived from operational requirements. The number of patients and area requirements per patient are coupled with the operational costs of staff to determine the floor area needed.

The initial USAF study (ref. 8) presumed a load of 10 patients and 2 attendants. The later investigation (ref. 9) showed that staff operational costs have a significant impact and that within a decade of operation, larger chambers operated less frequently, are the cost effective choice.

Statistics on chamber size and average area per patient for the USAF Clinical Hyperbaric Facilities (CHF) are compiled in Table 1.

TABLE 1 - PVHO SIZE and PATIENT LOAD

WPCHF (built in 1985, operational in 1987)
MAIN - 22' cylinder - 18 patients (21 sq.ft./patient)
EMERGENCY - 11' cylinder - 6 patients (16 sq.ft./patient)
LOCK - 11' cylinder

DGCHF (built in 1988)
MAIN - 23' sphere - 18 patients (23 sq.ft./patient)
EMERGENCY - 12' cylinder - 6 patients (19 sq.ft./patient)
LOCK - 12' cylinder

PNHCHF (planned for 1992)
MAIN - 20' sphere - 16 patients (20 sq.ft./patient)
EMERGENCY - 14' cylinder - 10 patients (15 sq.ft./patient)
LOCK - 12' cylinder

Table 1 suggests that the main treatment chambers of the future should accommodate 16 to 18 patients per dive. The experience at WPCHF has been 30+ patients per day and two dives per 8 hour shift. This level of usage supports the size of the main chambers listed in Table 1.

The required floor area of the main chamber is derived by multiplying the number of patients per dive by the area that the patients' chair or litter covers to arrive at an approximate total area. Additional area is set aside for clearance around the chair and litter and for aisles. Aisles are assumed to be 4 feet wide.

The area required for the litter and wheel chairs used in USAF CHF are:

litter dimensions = 30"W x 78"L (nominal 3'x 7')

chair dimensions = 22"W (nominal 3'x 3')

large wheel chair = 28"W x 45"L (considered as a litter)

The projected mix of chairs and litters is 50%. In the analysis of area requirements, the assumption of 100% litters or 100% chairs is made however.

Other floor layout considerations are:

1.) all patients must have access to at least one aisle,

2.) all aisles must lead to a door,

3.) the door is at least 5' wide and

4.) only one door is needed for patient entry.

The variations of configuration of a rectangular room that can accommodate 18 patients in wheel chairs is shown in Figure 1. Each of the chair locations is denoted by a opened box. The door is shown at one end only and is positioned external to the room for clarity. The door would preferably be located inside the chamber. A one foot clearance is allowed for the door movement. The size and shape selection criteria is to minimize floor area and door size. Floor area costs both in construction dollars and in operational gas expense. The larger the door, the greater the technical risk and potential cost.

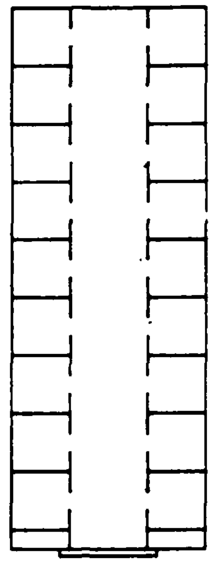
The top layout in Figure 1 requires the smallest floor area and the narrowest door. The 11 foot wide door shown in the middle layout is impractical and costly. To fit inside the room, the door would have to split and each segment would slide away from the other; not a practical approach. The all litter situation yields twice as many options of room shape. Figure 2 shows that the option in the upper left yields the smallest area and also requires the minimum door size.

The rectangular configuration selected is shown in the upper left of Figure 2. It is 27 feet long and 18 feet wide. A ceiling height of 10 feet is chosen. The area per patient is 27 sq.ft. This is generous compared to other steel CHF, see Table 1. The steel chambers offer less area and the floor area is circular shaped; a shape often difficult to fully use.

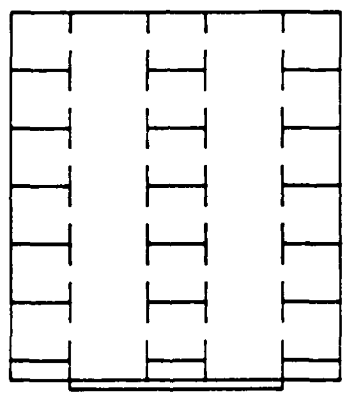
A layout showing the main treatment chamber and a lock is seen on Figure 3. A mix of chair and litter patients is indicated. The length of the lock is selected to give room to position patients without interference. The area of this lock is about 25% larger than the 12 foot diameter lock currently specified.

Figure 3 illustrates a three room combination similar in size to current CHF facilities. This sketch depicts a feature of concrete construction that steel cannot offer. Concrete chambers can be easily extended to meet size requirements. Additional rooms can be added and sizes adjusted without major design impact. Note also the absence of the rectangular passageways, a costly and technically difficult feature of current CHF designs.

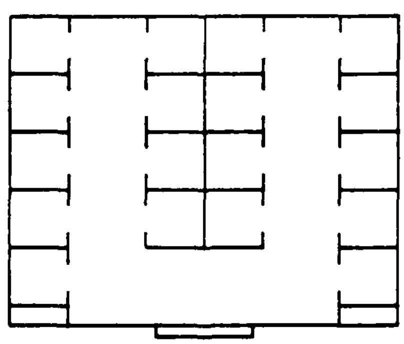
The study below concentrates on the design of the main treatment chamber. It is the largest and therefore the most costly component. The addition of smaller rooms pose no special problems not encountered in the design of the main treatment chamber. An artists drawing of the original concept for the main chamber is on Figure 4.



9 X 2
280 sqft 5' DOOR



6 X 3
323 sqft 11' DOOR



5 X 4
320 sqft 5' DOOR

SCALE = 12'

FIGURE 1 – CHAIR ARRANGEMENT OPTIONS

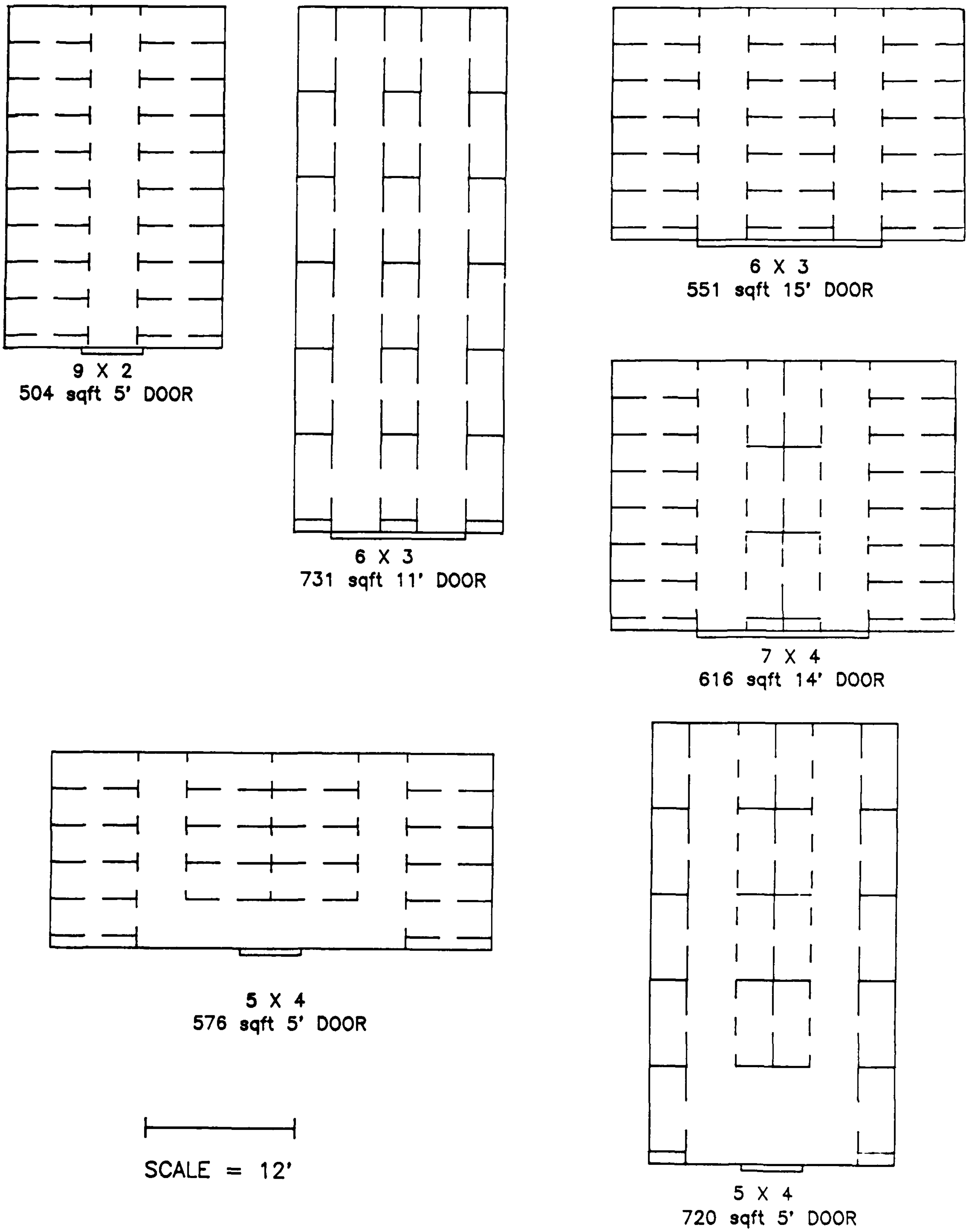


FIGURE 2 – LITTER ARRANGEMENT OPTIONS

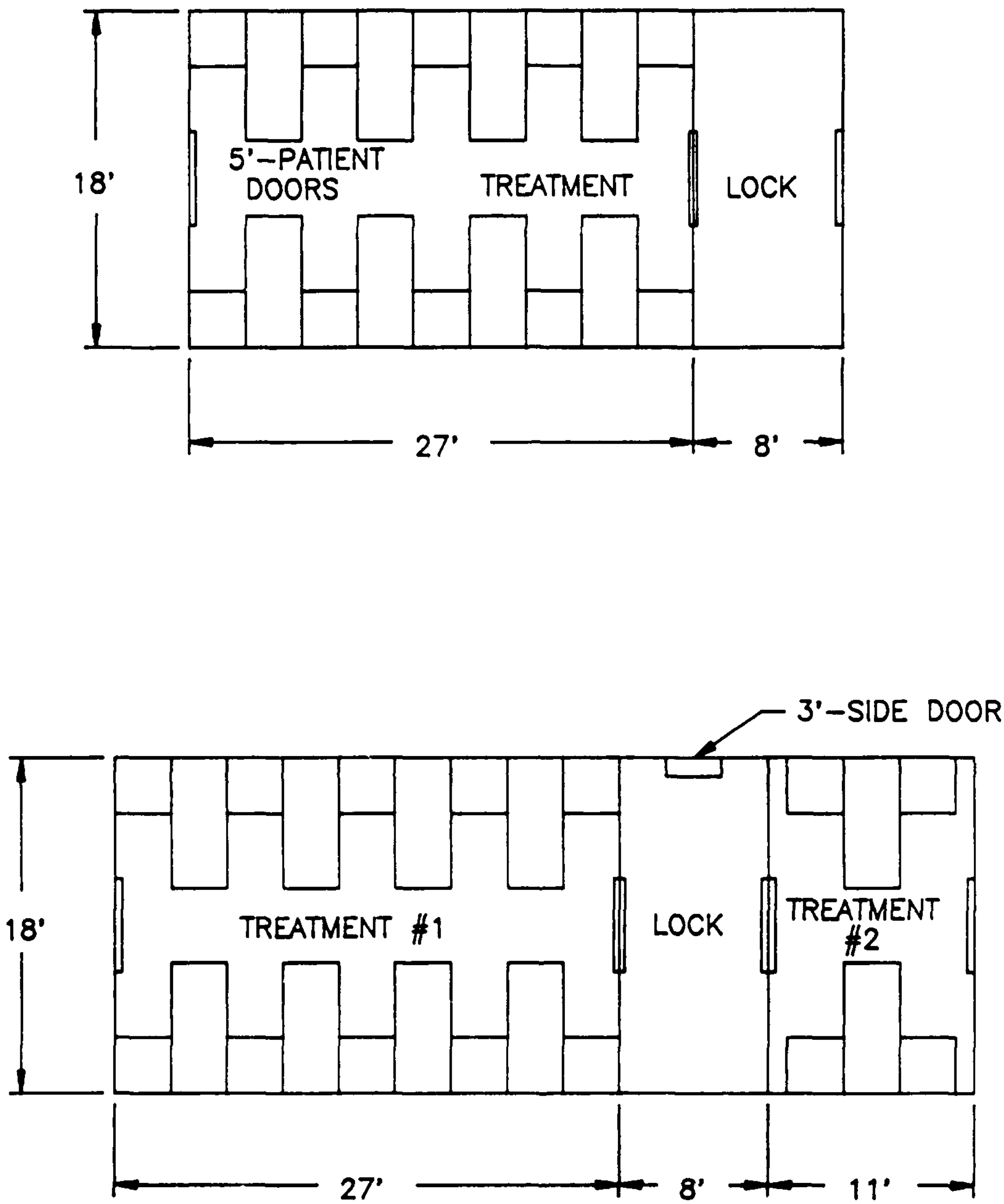


FIGURE 3 - TREATMENT CHAMBER LOCK COMBINATIONS

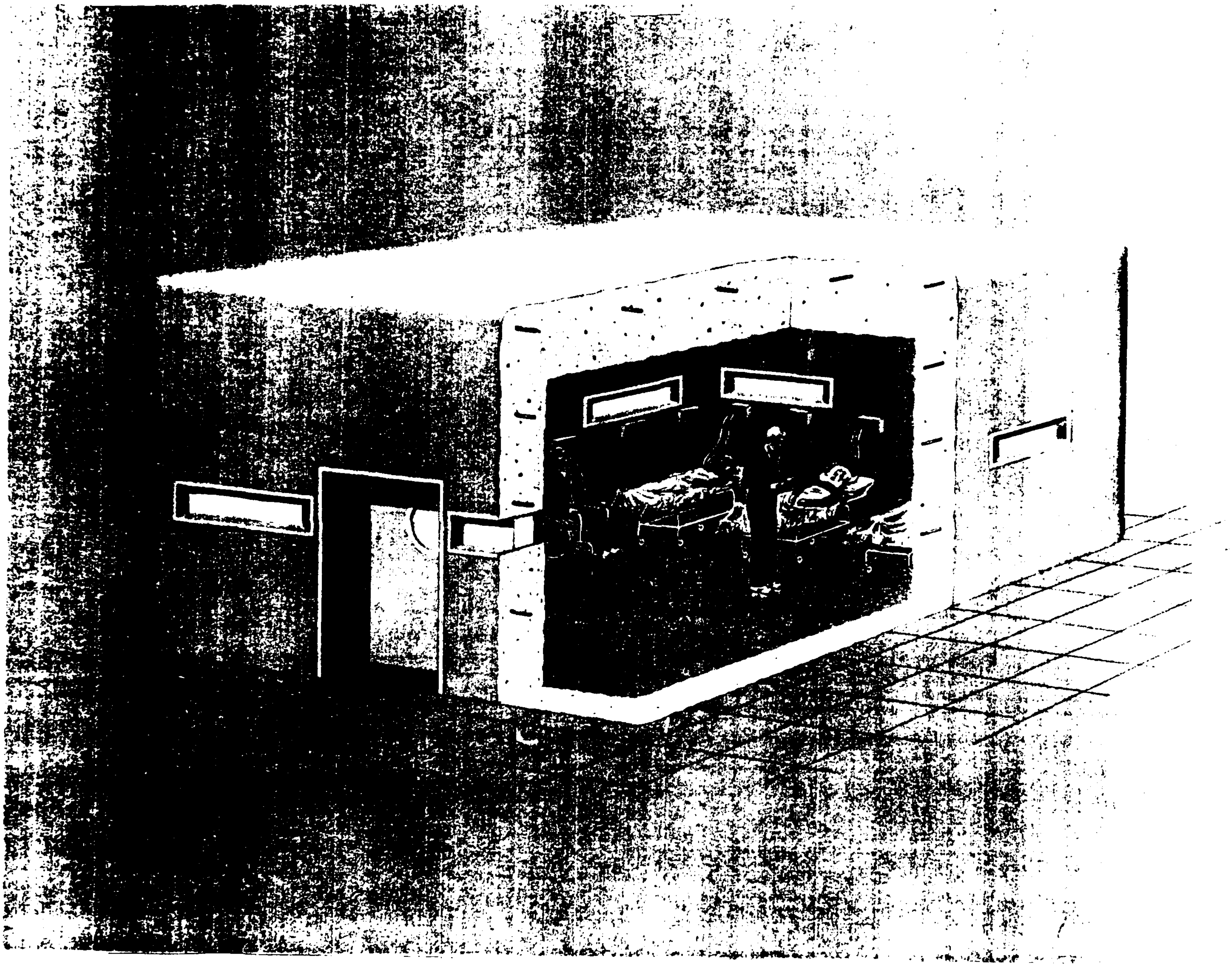


Figure 4   Artist's Concept of Main Treatment Chamber

FUNCTIONAL DESIGN

The functional aspects affecting the main chamber design include the patient load, already discussed, patient handling and movement, patient comfort and patient monitoring or viewing.

The main chamber should accommodate 18 patients. To ease the movement of patients into and within the room a large door and wide aisles should be provided. The desired door opening is 48-60" wide and 76-84" high. The door should be clear opening and should be flush with the floor to permit one attendant to move one patient. The lifting of chairs or litters across the door frame is to be avoided.

Patient viewing is improved with large windows. Current practice of 15" circular openings limits the observers field of view. Long slot windows provide a better viewing angle. The viewer experiences less fatigue as sight along the room becomes possible. Also the chamber interior lighting requirements may be reduced by use of slot windows as skylights. Slot windows should be specified for rectangular chambers.

The rectangular shape of the room will be less disconcerting to the patient than the curved walls of a steel CHF. It is more "hospital" like and less claustrophobic. The slot windows should further reduce patient anxiety.

The chamber is the key component in the PVHO system. Other components are the gas handling subsystem with pressurization, temperature and humidity controls, the communications subsystem, and the patient entertainment and operator-console interface. While each of these subsystems has some impact on the main chamber design only the piping influences the structural design. This impact is in the size of wall penetrations. Local reinforcements are a common feature in concrete construction. Penetration design requires attention to detail but it is not a new technology. Piping sizes to 8" can be readily accommodated.

A lining will probably be required to reduce sanitation problems. Microfissures will develop in concrete and may be a site for organic contamination. A stainless steel liner could be added after the walls had been poured or could be used as an integral form. A polymer concrete coating of the inner surface is an alternative to the stainless liner, however, flammability studies of the polymer concrete would be required.

STRUCTURAL DESIGN

The structural design of a rectangular prestressed concrete PVHO includes consideration of materials and design procedures. In the following, a brief discussion of factors that influence concrete strength are given. First the advantages of higher strength concrete are presented (ref. 12) followed by a discussion of concrete mix design. A brief discussion of the two conventional design approaches precedes comment on concrete fatigue.

The obvious advantage to higher strength concrete is its enhanced failure resistance to compressive stress. Other improvements include an increased tensile splitting stress, a higher elastic modulus and a much lower creep rate.

In the design of circular prestressed high pressure vessels the higher compressive stress can be utilized directly. The concrete is loaded in biaxial compression by the circumferential prestressing wires and a higher allowable concrete compressive stress translates into a higher operating pressure. The situation in a rectangular room is substantially different. The walls, ceiling and floor act very much like beams in bending. Prestressed beam design is more dependent on tensile than compressive strength.

As concrete compressive strength increases so does tensile strength. The tensile strength shows a proportional increase but seldom exceeds 6% to 10% of the concrete compressive strength. Unfortunately much of the added tensile strength from high strength concrete is unavailable as the ACI Code gives credit on the square root of compressive strength. Allowable tensile stress for 6,000 psi concrete is 465 psi whereas 18,000 psi concrete has a tensile allowable of only 805 psi (465 * sqrt[18000/6000]), instead of a proportional 1395 psi. The lack of proportionality in tensile strength significantly reduces the usefulness of high strength concrete for rectangular PVHOs.

High strength concrete offers a higher elastic modulus, an attribute used by high rise building designers, and reduced shrinkage and creep. Creep and shrinkage are difficult to separate experimentally since both are time dependent. Creep is the time dependent deflection due to stress. Shrinkage is contraction due to drying and chemical change (hydration) of the concrete. Since creep and shrinkage reduce the size of the concrete, stress in the tendon is reduced and some of the prestress advantage is lost. Low creep and shrinkage in the concrete is therefore desirable.

The design of the concrete mix determines concrete strength. Important factors are the water to cement ratio, the amount of cement, aggregate strength and the grading of aggregate sizes. The strength of concrete is inversely related to the water/cement ratio (w/c). The ideal stoichiometric mixture of water to cement for complete hydration is 0.18. As more water is added the w/c increases and strength drops. Conventional concrete has a w/c = 0.45. A lower w/c ratio produces a stiffer mix, one that is difficult to place and consolidate.

Concrete strength increases with time. Conventional practice is to design using the 28 day strength (f'c). In 7 days concrete develops 60% of the 28 day strength, but strength will increase to an asymptotic value over a period ranging from 50 to 200 years. A water or steam bath during the initial cure produces higher strengths.

The other main component in prestressed concrete is the tendon. Tendon steel is available in three forms - wires, strands or bars. Seven strand wires is most commonly used. Nominal strength is either 250 ksi or 270 ksi. Seven strand wire is readily available and its characteristics are well understood.

There are two considerations common to design of concrete structures: strength and serviceability. The strength of the structure is of similar interest to the designer of steel PVHOs; however serviceability is a new topic.

Concrete design can use either ultimate or elastic strength principles, (ref. 13, 14). The prestressing concept provides the basis for both ultimate and elastic design. Prestressing transforms a brittle material into an elastic one through precompression.

The "balanced condition" concept is used to size tendon steel. It balances the concrete in compression and the steel in tension such that the crushing strain in the concrete and the tendon yield strength develops simultaneously, at the same load. Ductile behavior occurs if the yield strength of the tendon steel is reached before concrete crushes. An under-reinforced section is where the steel fails before concrete. The section is over-reinforced when concrete strength is exceeded before tendon yield strength is reached.

The ultimate strength method is the preferred design practice available in the ACI Building Code, (ref. 15). Load factors are used to account for the uncertainty of load conditions and capacity reduction factors are applied to allow for understrength effects in the materials. This approach introduces safety factors on both the loads and strength.

The load factors specified are 1.4 times the dead or constant load and 1.7 times the variable load on the structure. The dead load includes self weight. A controlled internal pressure typical of a PVHO could also be thought of as a dead load although since it changes, it would likely be treated as a live load. The 1.4 factor accounts for variation in density of concrete and the variability in cast section size.

Live loads are variable loadings. Live loads include wind, snow, cars on a bridge and other loadings that change suddenly. The uncertainty in magnitude of these loads and the statistical variation increases the load factor to 1.7 times the predicted load. The pressure load on PVHOs was treated as a live load in the design exercise described below. Earthquake loads are a special case of live loading and because of the large uncertainty in load magnitude the load factor is increased further to 1.9.

Capacity reduction factors reflect the variability in material strength when the concrete is subjected to different loadings. Axial and flexural load behavior is well known and accordingly the strength is reduced to 90% of the nominal strength. On loadings that have been found to lead to premature failure the strength is reduced more. The reduction factors are 0.85 for shear and 0.70 for bearing stress.

The primary advantage of the ultimate strength design method over the elastic method is it produces a more efficient structure requiring less material. It also accounts for uncertainties in live loads. The ACI rules are based upon extensive experimental evidence and have produced safe structures. The ultimate strength method is generally preferred by civil structural engineers.

Disadvantages to the method are attributable to its experimental foundations. As stated above, concern has been expressed that a high strength concrete may behave differently than conventional concrete and therefore criteria that were experimentally derived from lower strength concrete may lead to unsuitable structures. A second disadvantage with ultimate strength design is the difficulty in developing mathematical models of structural details. Ultimate strength implies a design based upon prediction of failure, and failure is generally preceded by a nonlinear response to increasing load. To mathematically model the behavior of a structure to failure is at best difficult. The nonlinearities of concrete cracking and crushing, along with steel rebar and tendons yielding are a test of analytical tools. Another factor that detracts from the ultimate strength method is an overly conservative load factor applied to a well behaved and predictable load such as the internal pressure in a PVHO.

The ultimate load factor method was used in the preliminary design of the rectangular concrete PVHO.

The elastic strength is the older method of design. It is allowed in the ACI Code, but is relegated to an Appendix. Elastic design uses only the straight line portion of concrete stress strain curve. Actual service loads (load factors = 1.0) are used and reduced allowable stresses are specified. The nominal allowable concrete compressive stress is 0.45*f'c. This method of design lends well to math modeling using finite elements. The design of steel PVHOs and the ASME Boiler and Pressure Vessel Code are founded on the elastic strength method.

The preliminary design for the rectangular concrete PVHO was evaluated using the more conservative elastic strength method.

As stated above both strength and serviceability are of concern to concrete designers. Serviceability is related to deflection and surface cracking. Deflection is limited by the ACI Code depending on the significance of the deflection. Typical limits range from (span length)/180 for noncritical applications to (span length)/480 for members that influence the structural performance of adjacent structure.

Surface cracking is controlled by restricting the tension in the concrete. No discernible cracking will develop if the concrete tensile stress less than 5*sqrt(f'c). Concrete cracks when its tensile stress reaches its modulus of rupture. Crack spacing and width depend on tendon stress level, how tendons are placed, concrete cover over tendons and the grade of steel used in the tendon. The ACI Code limits surface crack opening to 0.013" (< < 1/64") for exterior surfaces and to 0.016" for interior. Tighter tolerances are given in "critical appearance" locations where limits on crack width are reduced to 0.005". Surface cracking may not be a significant issue if the room is lined with a thin stainless steel vapor and gas barrier.

Fatigue is a major consideration in the design of steel vessels subject to fluctuating pressure loads. Many PVHOs are designed with additional wall thickness for the sole purpose of reducing alternating stresses below the endurance limit. Fatigue in prestressed concrete is of much less concern. Tests have shown that an unlimited number of cycles within the operating range will not produce fatigue cracks. Concrete fatigue does not occur in prestressed sections. Failure occurs in tendons after overload has caused massive concrete cracking. Concrete is a notch insensitive material. Hence, geometric discontinuities in the concrete due to holes or changes in section are not considered to affect its fatigue strength.

Tendon stress varies only slightly under pressure load. The nominal stress variation is 10 ksi on a prestress of 150 ksi. There is little possibility of fatigue failure of steel as long as concrete doesn't crack. If concrete cracks, local stress concentrations in wires may lead to fatigue failure.

"If the precompression in a prestressed concrete member is sufficient to ensure an uncracked section throughout the service life of the member, the fatigue characteristics of the prestressing steel and anchorages are not likely to be critical design factors. Further in a properly designed unbonded member, it is almost impossible to achieve a condition for which fatigue characteristics are important. Consequently, fatigue considerations have not been a major factor in either the specification of steel for prestressed concrete or the development of anchorage systems. No structural problems attributable to fatigue failures of the prestressing steel or anchorages have been reported in North America." (ref. 16)

QUALITY ASSURANCE

A major stumbling block in the acceptance of prestressed concrete for PVHOs is the extent and adequacy of quality assurance (QA). Concrete QA is notably different than that used in steel pressure vessel construction. Unlike steel, that is ordered from a mill to a standard specification, concrete is mixed to the designer's specification often in plants distant from the construction site. The quality of concrete is influenced by many factors that are irrelevant in steel construction. In concrete construction, inspections are required starting at the batch plant and extending through the final cure.

Exacting QA has been developed for high strength concrete. The consequences of an understrength batch of concrete in high performance building columns are financially devastating. Quality is of highest priority in high strength applications. The lessons learned for high strength concrete can be applied to concrete of all strengths (ref. 17).

The QA process begins with the mix design. Concrete mix design is conventionally based upon the weight of mix ingredients. Good mix design is compromised by unpredictable variations in the materials. In an attempt to control variability, some batch plants are using concrete design software. The computer software combines empirical formulas for the weights of material to be used with statistics developed of the material on hand at the mix plant. The plant foreman answers queries about desired end properties, such as strength and characteristics of the cement, fly ash, sand, stone, and admixtures. The software selects aggregate proportions and amounts of ingredients to produce the correct mix.

The second step in assuring quality concrete is to develop trial mixes. The most important factor for high strength is water/cement ratio. Three different w/c ratios should be tested to confirm the mix will have adequate strength. Aggregate size and aggregate strength variation will also affect strength. High strength concrete requires strong aggregate in the 3/8" to 1/2" size. Quality concrete aggregate may have to be imported if local sources are low grade.

In-process QA is mandatory for consistent quality of concrete. At the batch plant, aggregate should be washed to reduce silt, clay and fines. Sampling of the water content of all mix ingredients including aggregate, is required. A record of the amount of ingredients, the time the batch is mixed and temperature of ingredients should be maintained. Tolerances should be established in connection with the trial batch program. Mixing times should be taken from mixer tests, not from experience.

Job site QA should include monitoring of concrete, steel, forms, placement and curing. Each concrete delivery should be documented. A record of truck transit and hold time, slump and temperature of mix and air temperature at the site should be maintained by the site QA inspector. It is recommended that test samples be taken from each truck. The usual procedure is one sample per 100 cu.yd. but since a concrete PVHO requires about this amount of concrete in total, more sampling is needed. The inspector should control or prohibit the addition of water to concrete on the trucks.

The QA requirements for reinforcing steel and tendons begin with delivery. Tendons are delivered in rolls thousands of feet long. Care must be taken to prevent kinking and permanent twisting. The tendons should be greased to prevent corrosion and to insure correct post-tensioning. Bar and wire reinforcement should not be tack welded and any welding should require preheat.

Accurate placement of the reinforcing bars, tendon ducts and concrete is needed to insure good quality. Pumps or conveyors should be used for concrete placement. Vibration should be required and vibration times recorded. If vibration is not practicable, superplasticizers (water reducing agents) should be used.

Adequate strength depends on good curing conditions. It is essential that temperature and moisture content be maintained to insure hydration of cement. Because of high cement content, higher strength concrete can develop large thermal gradients during cure. These gradients can lead to internal cracking. Temperatures in the center of thick sections have been measured at 200 degree F. Temperature gradients of 30 degree F per foot are not unusual. The concrete should be insulated to prevent thermal stresses from developing.

Equally important to a good quality concrete is moisture content control during cure. High strength concrete requires water or steam curing. Total immersion is recommended for low strengths also. Fog curing is an acceptable alternative, but intermittent drying of the concrete cannot be permitted. Records of cure times and temperatures should be maintained.

Visual inspection is about the only reliable NDE method available. The inspector visually checks placement of forms, tendon ducts and rebar. The reinforcing should have sufficient strength to resist flow of wet concrete without movement. The inspector monitors transit time of trucks, temperature of mix and placement of mix, time of vibration and insures the water or fog curing equipment is promptly installed and maintained.

Attempts to use ultrasonics (UT) to detect flaws in concrete have been tried for 30 years without success. Success has been limited because the air pockets in concrete scatter and absorb sound waves (ref. 18). Recent research at the National Bureau of Standards offers hope for a concrete UT inspection tool. It was discovered that small steel balls dropped on concrete produce signals correlatable to flaws. A field unit that uses a spring loaded impactor is under development.

Testing of the final structure is a major assurance of quality. In prestressed concrete the post-tensioning operation produces the highest stresses on both the concrete and the tendons. During prestressing steel is tensioned to 85% of its ultimate strength and concrete to 60% of the compressive strength. Normal operating stress in the tendons is only 60% of ultimate while concrete can be loaded to only 45% of f'c during operation. The high post-tension stresses gradually are reduced to operating levels as concrete creeps and shrinks and the tendons relax. However during post-tensioning the structure has undergone a proof test of 1.4 times the tendon and 1.3 the concrete allowable strengths.

A hydrostatic or pneumatic proof test to 1.15 times the design pressure is also proposed. This is consistent with ASME Section III, Division 2 requirements and operational constraints that make pressure excursions highly improbable. Testing to 1.5 may lead to irreversible crushing of concrete.

PROPOSED DESIGN

Two alternatives were considered. The first was a design that used prefabricated prestressed post-tensioned concrete panels. The concept was to use standard components that were shop fabricated in controlled conditions and assembled in the field. Shop fabrication insured precise concrete mixes, accurate tendon placement, thorough vibration, steam curing, and correct post-tensioning. Cranes would be used for field assembly of the prefabricated panels.

The panels required high strength concrete and relied on strength enhancement from a biaxial stress field induced by tendons lying in both directions. Thick sections were required to develop bending resistance.

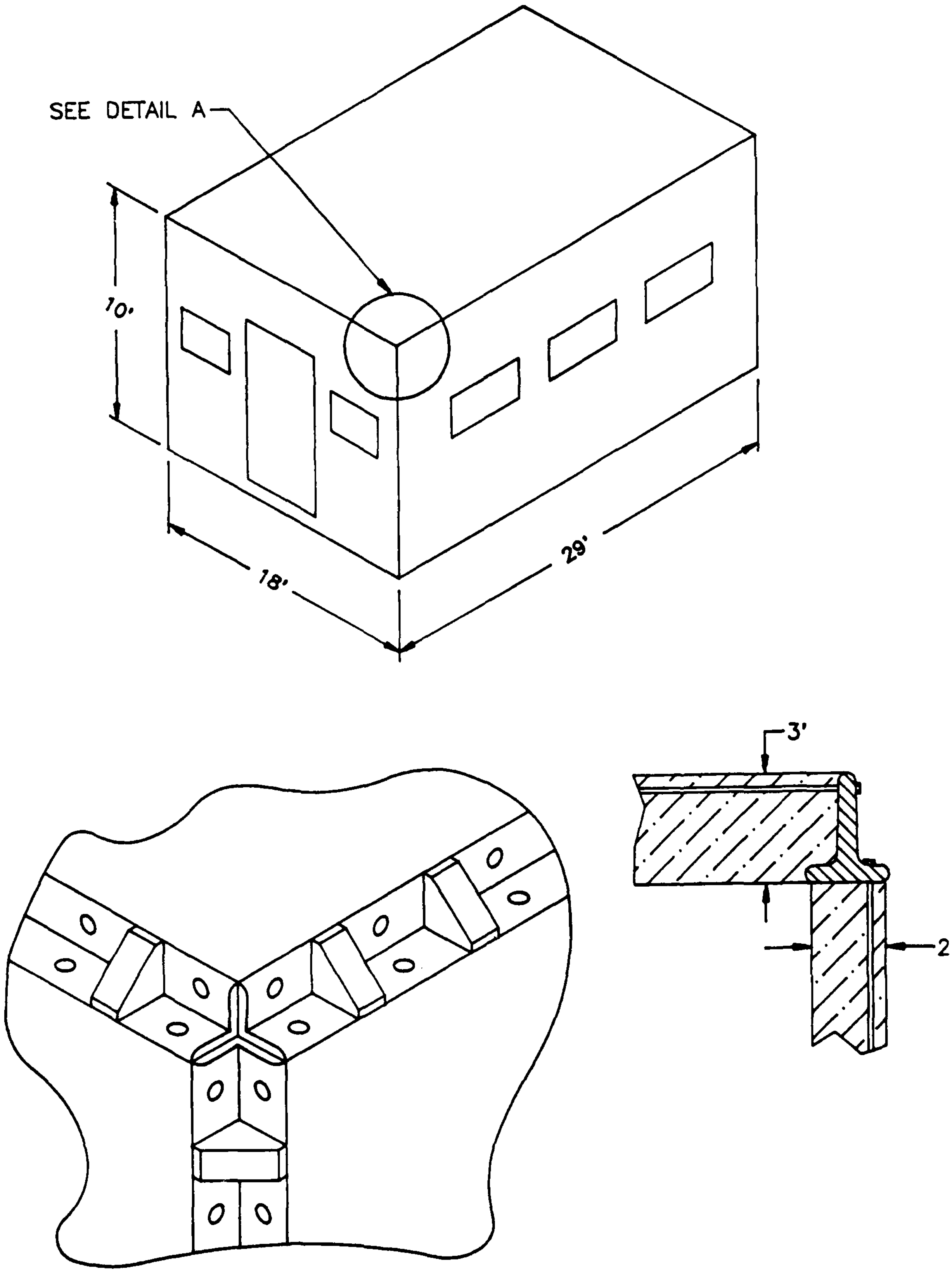
The concept encountered difficulties with load transfer at corners. Substantial steel members were needed to resist bending. Figure 5 shows the corner detail. The concept was abandoned because of excessive cost.

An alternative design was developed. It was conceived as an assembly of conventional "T" beam sections fitted together to form a box section. A box section would be made from four "T" beams arranged at right angles with the webs to the outside. The top of the flange on the "T" beam becomes the inner wall of the PVHO. The web of the "T" beam extends around the box as a structural girdle. The critical dimension is the maximum span length, the 18 foot distance across the room. Box sections would be stacked end-to-end to form the room. Since the across-room span governs design, the length of the room can be increased by adding "T" beam segments. End walls would be similar to the "T" beams in the side walls but because of the shorter span would be stressed less.

This concept proved useful for sizing the "T" beams, however, the actual structure would be poured as an integral unit. Each beam was designed to carry a 6 ATA internal pressure. The flanges of the beams are the ceilings, floor and walls of the room. The wall can also be considered as a two-way post-tensioned slab, a conventional concrete member.

The structural sections comprising the ends of the room will have the same dimensions as the side "T" beams. However, buttresses are added to reinforce the door. Both the door and window openings would also be reinforced with steel plate and rebar. The concept is shown in Figure 6.

Preliminary finite element analysis of the concept showed that the buttresses at the doors introduced a torque on the top and bottom "T" beams. Prestress of the buttresses caused a shortening that in turn tilted the "T" beams away from the room. In anticipation that this effect may prove detrimental to the final design, a slight design modification was made. Longitudinal members that connect the outside "T" beam to the adjacent beam were added. Figure 7 shows the alternate concept.



DETAIL A

FIGURE 5 – POSTTENSIONED FLAT SLAB CONCEPT SHOWING CORNER DETAIL

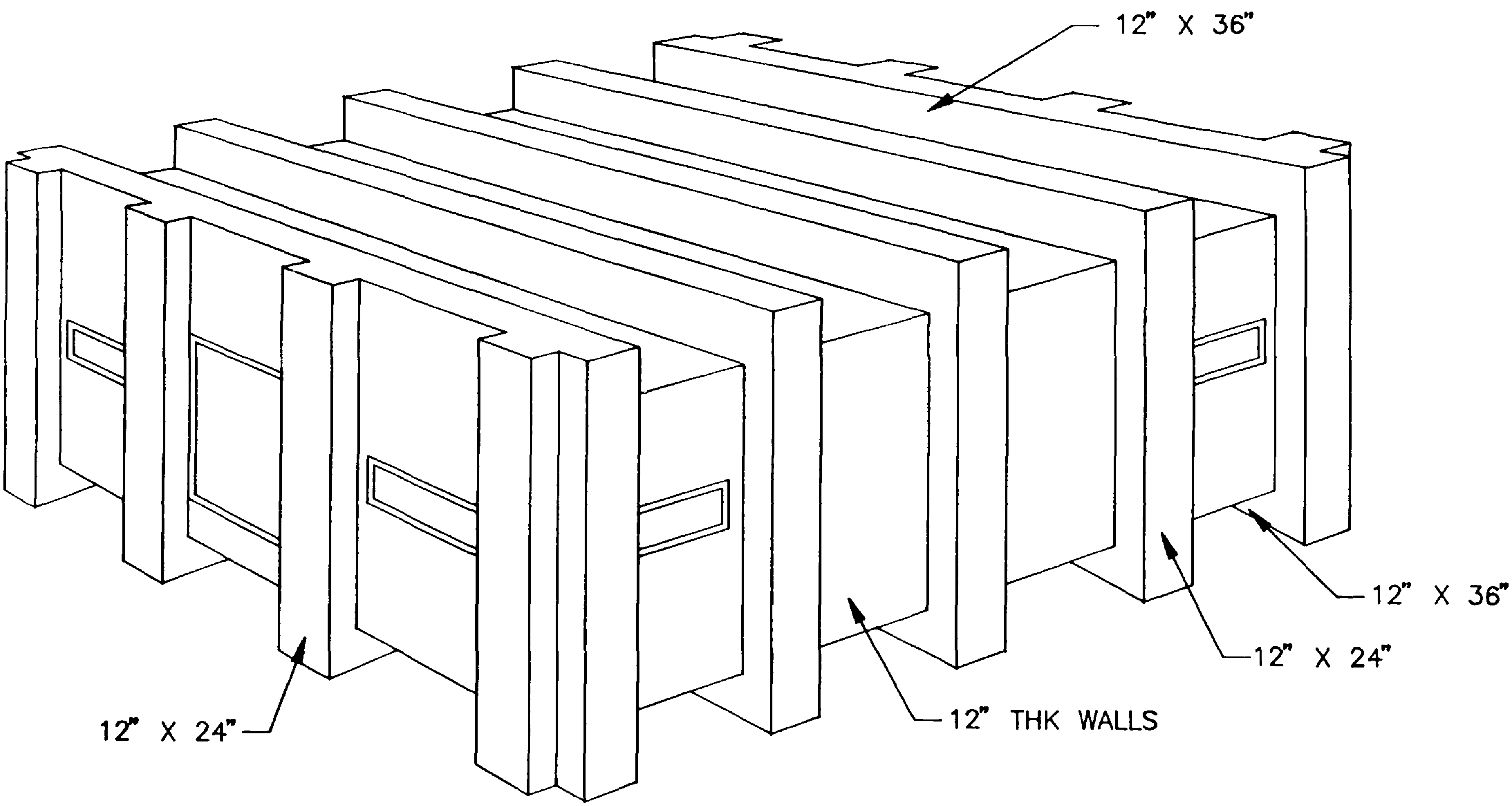


FIGURE 6 – POSTTENSIONED "T" BEAM CONCEPT

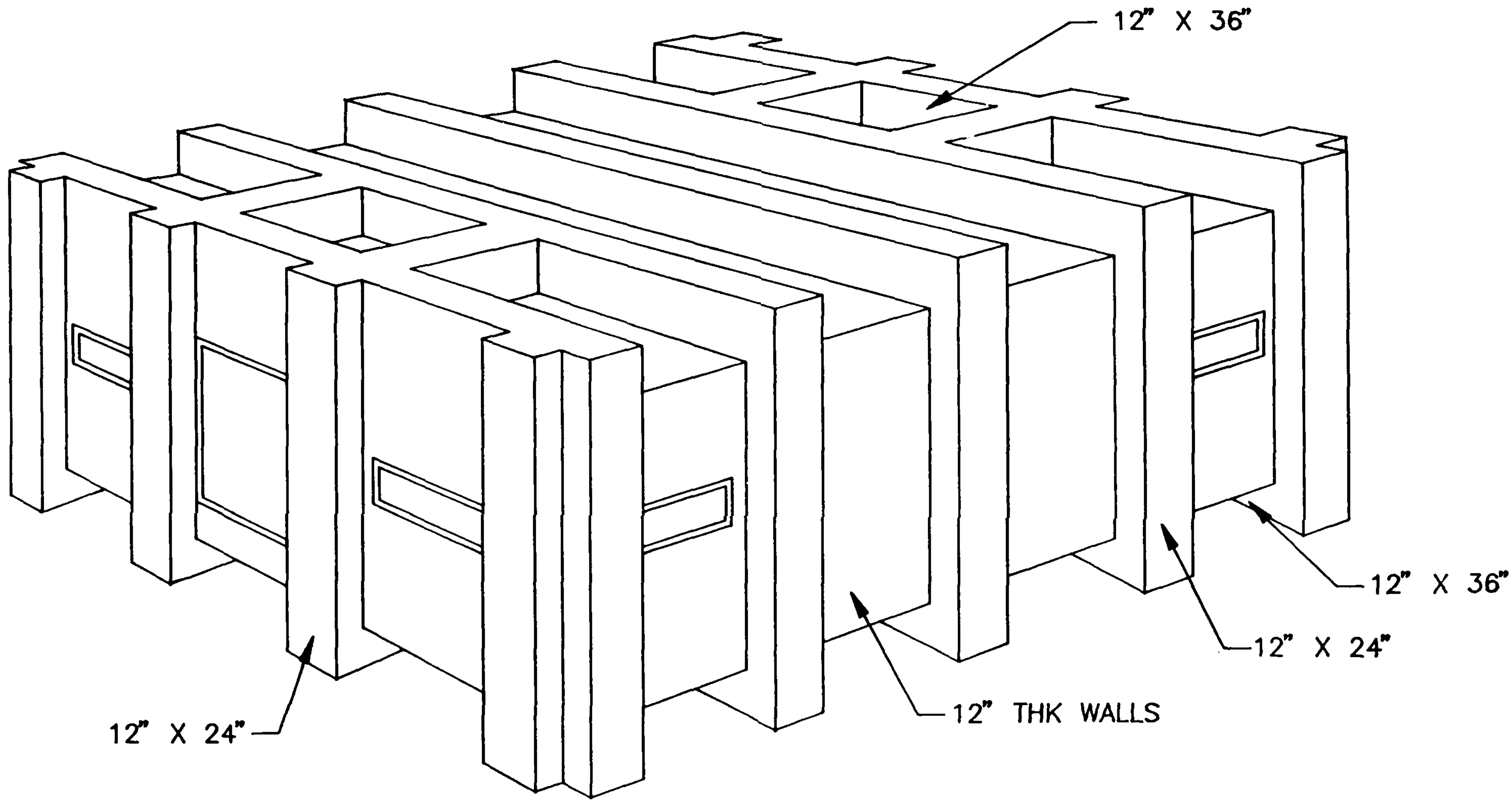


FIGURE 7 – POSTTENSIONED "T" BEAM CONCEPT ALTERNATE

PRELIMINARY DESIGN

The preliminary design of the large treatment chamber was made to satisfy ACI ultimate strength criteria. The "T" beam was 18 foot long and 6-1/2 foot wide. The live loading was the design pressure of 6 ATA or 10,584 psf (pounds per square foot). The assumed concrete strength was 6,000 psi.

The design was checked with a special purpose post-tension computer program (ref. 19). The design was verified both as a post-tensioned "T" beam and as a post-tensioned flat slab. Reinforcing to produce a balanced design was determined by the computer program.

DETAILED DESIGN

Typically, a preliminary design is made with a number of simplifying assumptions. The purpose of the preliminary effort is to size major components. Once sizes are approximated, details are examined more closely. The simplifying assumptions made in the preliminary design were:

1. the "T" beam is fixed at the ends. While this assumption is reasonable for preliminary sizing, the corners are not infinitely rigid and some deflection will occur. The detailed design examines the biaxial post-tensioning effects on local stresses in the corners.

2. the beam has no side restraint. This also is a necessary assumption inherent in modeling the room as beams. The complementary flat slab preliminary design calculations account for the effect of biaxial prestressing of the walls and acts to confirm the "T" beam design. The preliminary dimensions for the members are taken as the maximum required to satisfy ACI requirements for either the "T" beam or the slab.

3. the short span "T" beam represents a worst case for the walls and the ends will be adequate if the same dimensions are used. This assumption is difficult to justify since the ends have a large opening for the door and smaller openings for the slot windows.

Given these assumptions, confirmatory analysis is needed. The detailed analysis is however preliminary. It also makes simplifying assumptions. The assumptions made are appropriate in a feasibility study, but would require rigorous evaluation in a final design study.

The preliminary design used ultimate strength design principles. Confirmation in the detailed phase implies a major analytical effort to derive the ultimate burst resistance of the room. Such is beyond the scope of this feasibility study. The alternative elastic strength design method is more amenable to finite element analysis. It is used in the following. Note however that some differences may develop as the two design methodologies are not necessarily consistent.

The detailed design is directed at a number of issues. Confirmation of gross dimensions is desired. Insight into how the room deflects under no load and design pressure is valuable. The stresses at the intersection of the "T" beams needs definition. Deflection, load transfer and stresses at the end to ceiling location is of particular interest as it may force the alternate design, Figure 7, to be used. Finally nominal stresses in the inside corners and around openings is useful in confirming the adequacy of the proposed design.

FINITE ELEMENT ANALYSIS OF THE MAIN TREATMENT CHAMBER

There is considerable interest in the techniques used for modeling of concrete structures (ref. 20). Research is directed at sophisticated material models and solution algorithms that can account for the creep, cracking and crushing in concrete and the relaxation and yielding of tendon strands. However, in this study, the finite element method (FEM) is confined to a linear static analysis. This simplification is consistent with the elastic strength method of the ACI Code. The ANSYS finite element program is used (ref. 21).

A finite element model of the main treatment chamber is shown in Figure 8. The model is colored to indicate major structural components. The walls of the room are light blue, the reinforcing buttresses are purple and the door and windows are red. Figure 9 shows these main components individually. The room is shown in cut-away to highlight the door and window openings.

The model includes concrete, reinforcing bars, and tendons. Acrylic plastic slot windows with a clear opening of 48" wide and 12" high are shown in the ends. Additional windows can be added in the sides or as skylights in the ceiling. The windows would be located between the buttresses. The steel doors are shown at either end of the room. The doors have a clear opening 60" wide and 84" high.

The uniformity of the geometry and loading allow for a simpler, smaller section of the room to be analyzed. The room can be quartered and still provide all the analytical results of the full model. The room is quartered about two vertical orthogonal symmetry planes running through the center of the room.

The quartered section is shown in Figure 10 from two viewing angles. The window is now shown in green and only 1/2 of the door remains. The buttress coloring indicates the orientation of the prestressing tendons. Tendons in the purple buttresses run horizontally across the room. The red buttresses contain vertical tendons and the dark blue corners represent the anchorage regions for both horizontal and vertical tendons. The concrete shown in dark blue is expected to have high biaxial compressive stress.

The modeling is done with three dimensional brick elements. A reinforced concrete element is used except for the window and door which are modeled with standard 8 node brick elements. Tendon and reinforcing steel are included in the concrete element by modification to the element's stiffness. The merging of the tendon with concrete to get a composite behavior is a simplifying assumption. In a detailed design analysis the tendons would be modeled individually and separate from the concrete. The concrete element also has nonlinear creep and crushing capability, features not needed for this study. The 1/4 symmetry model contains 4158 elements. The elements are 8" cubes.

The model includes considerable detail, yet it is not sufficient for detailed design confirmation. Numerous simplifying assumptions were necessary to permit the problem size to be reduced and a solution obtained. As mentioned above, the tendons are included as bonded reinforcement averaged across the element. Actual tendon placement will be at the extreme top and bottom of the "T" beam and the tendons will be greased and unbonded. The window and door are treated as rectangular cutouts. The radius at corners of the window and door were ignored. The window and the door frames are not included nor is the reinforcement steel that will transfer the door and window loads into the concrete. The stirrups that are needed to control diagonal tension in the corners of the room are not accounted for. In spite of these limitations the model of the main treatment chamber is sufficiently detailed to give an overall displacement response and provide some insight into stress levels.

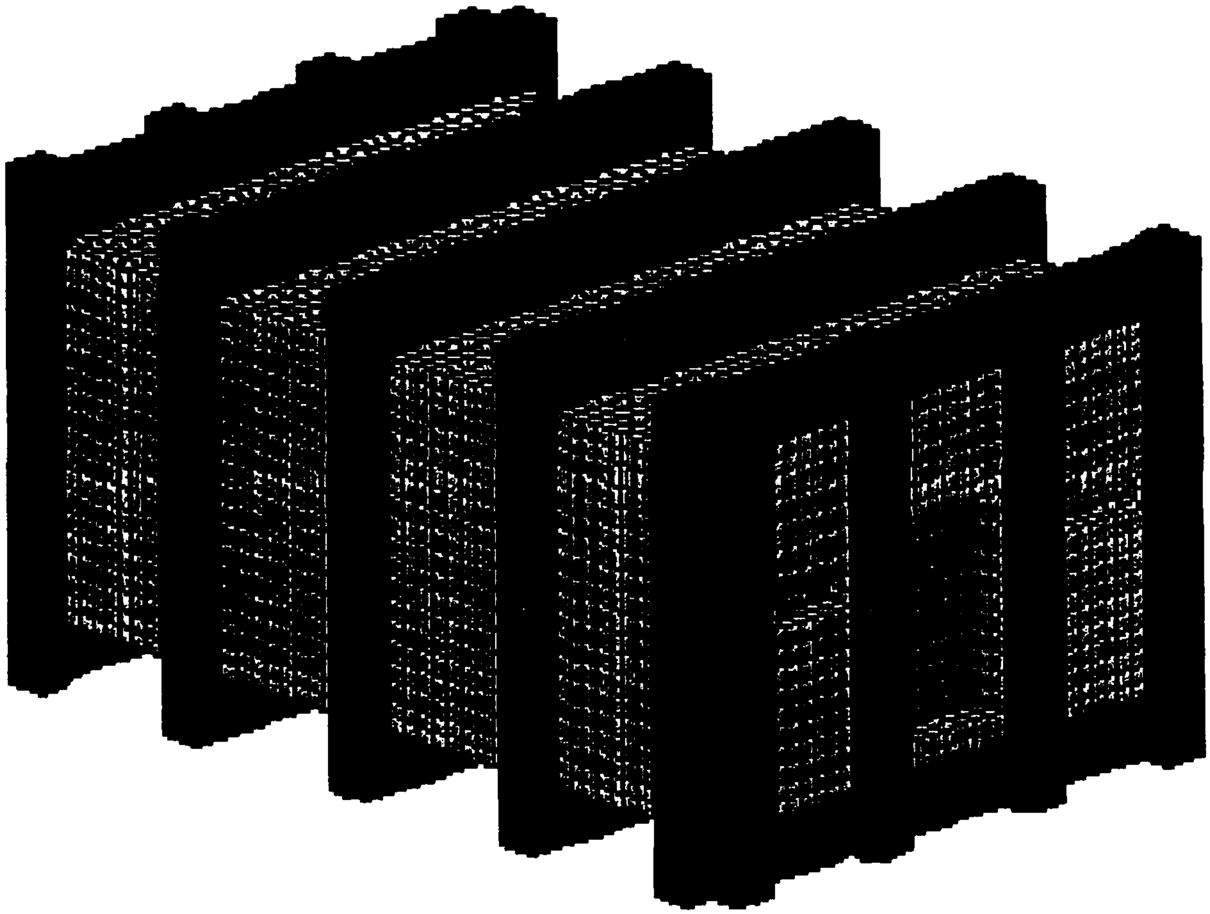


Figure 8 Conceptual Design of Main Treatment Chamber

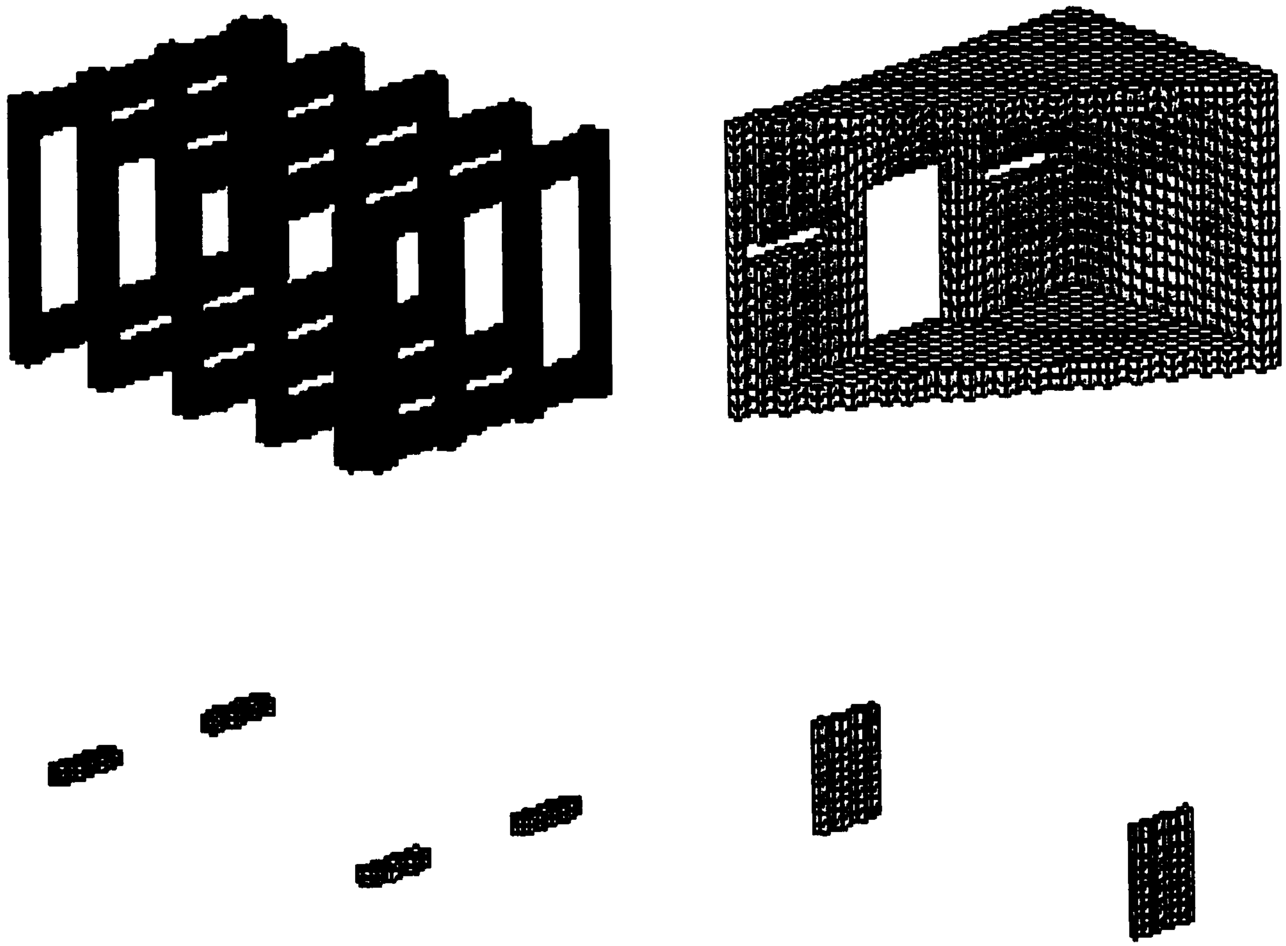


Figure 9 Buttresses, Wall Cut-Away, Windows & Doors

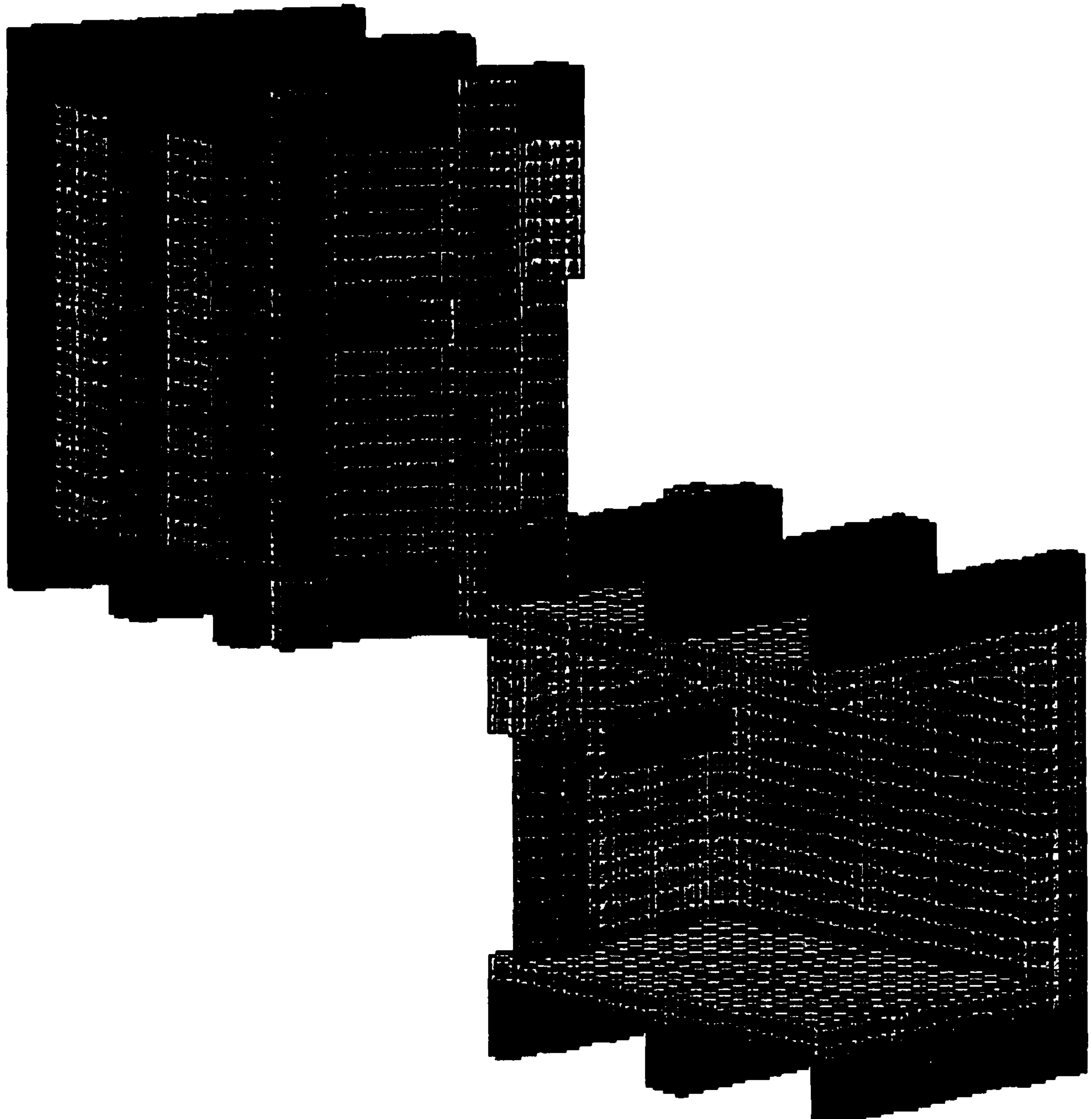


Figure 10 Rectangular Concrete PVHO Structural Model (1/4 symmetry)

Two load cases are studied. The post-tensioning case is modeled by forcing a thermal contraction in the tendon reinforcing steel. The second load case superimposes a 6 ATA pressure on the post-tension stresses. Gravity loads are included in both load cases. Symmetry boundary conditions are applied along the cut planes. A vertical restraint is established at a few locations along the bottom of the floor beams.

The FEM results of the load cases are shown in Figures 11 to 20. Figure 11 shows two views of the displacements induced by post-tensioning. The outlines of the model are magnified to illustrate behavior. The post-tensioning causes a contraction of the top beams at the corners and a drop in the center of the ceiling. A shortening of the end beams also leads to a bowing-in of the ends. This bowing effect led to the alternate concept shown in Figure 7. It was postulated that the addition of a longitudinal member between the end buttress and the first transverse ceiling and floor beam would counteract this end bending. The stress results show that this additional member was not needed.

The addition of internal design pressure causes the room to expand, see Figure 12. Since the bottom of the room is constrained from vertical movement, all expansion appears in the ceiling. This assumption may be altered to reflect the actual foundation supports.

The stresses in the concrete are shown in Figures 13 and 14. A combined von Mises stress is used to develop an overview of stresses. The von Mises stress is a derived stress that has only positive values. It is not applicable to concrete failure, but acts to direct attention to specific regions of high stress. The most highly stressed regions are colored red. Lesser stresses are shown in progressively darker colors. Low stresses are in blue. The buttresses have the highest stress. Stress is concentrated in the anchorage regions, but the highest stress develops just above the lower anchorage and is related to the vertical restraint placed along the lower beams.

A more detailed examination of the stresses, both tensile and compressive, is made for both the buttresses and walls. The stresses in the buttresses are displayed in Figures 15 and 16 as colored contour plots. The values of the contours are keyed to numerical values in the right hand column. The principal compressive stresses are displayed in the upper left and the principal tensile stresses in the lower right. Figures 17 and 18 show the same stress categories in the wall sections. The stress contours are superimposed on the displaced geometry.

Interpretation of a finite element analysis (FEA) derived stress is a bit more involved than a simple comparison to the ACI Code allowable values for tension and compression. The ACI Code values are applicable to a nominal (membrane plus bending) stress. The FEA produces the total stress at a point which includes both the nominal stress and other isolated stresses. The ACI Code provides scant guidance on an allowable value for local isolated stresses.

Unlike the relatively straightforward ACI stress allowables, the ASME Boiler and Pressure Vessel Code, (ref. 4), goes to considerable length to distinguish stress categories. Average and point stresses are differentiated. Under each of these categories, subcategories for primary, primary plus secondary, and peak stresses are defined. Different allowables are given for each subcategory.

A further complication is the different stress allowables for different loading conditions. Both the ACI and ASME allow higher stresses during the post-tensioning operation than for normal operations.

Categorization of the FEA stresses into subcategories is beyond the scope of this study. The usefulness of the FEA stress data lies less in the absolute numeric values and more as an indicator of:

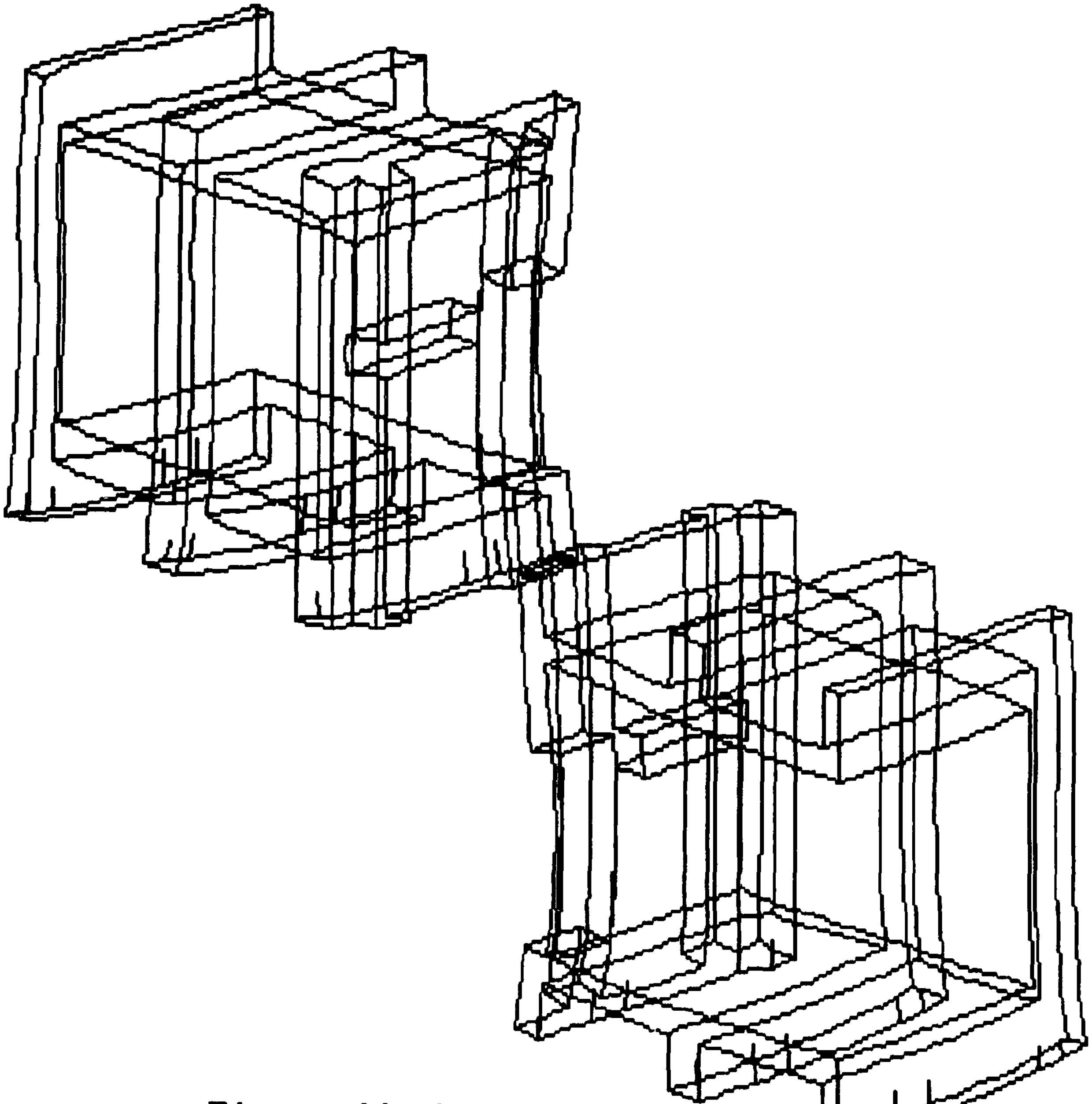


Figure 11 Displacements - PostTensioned Case

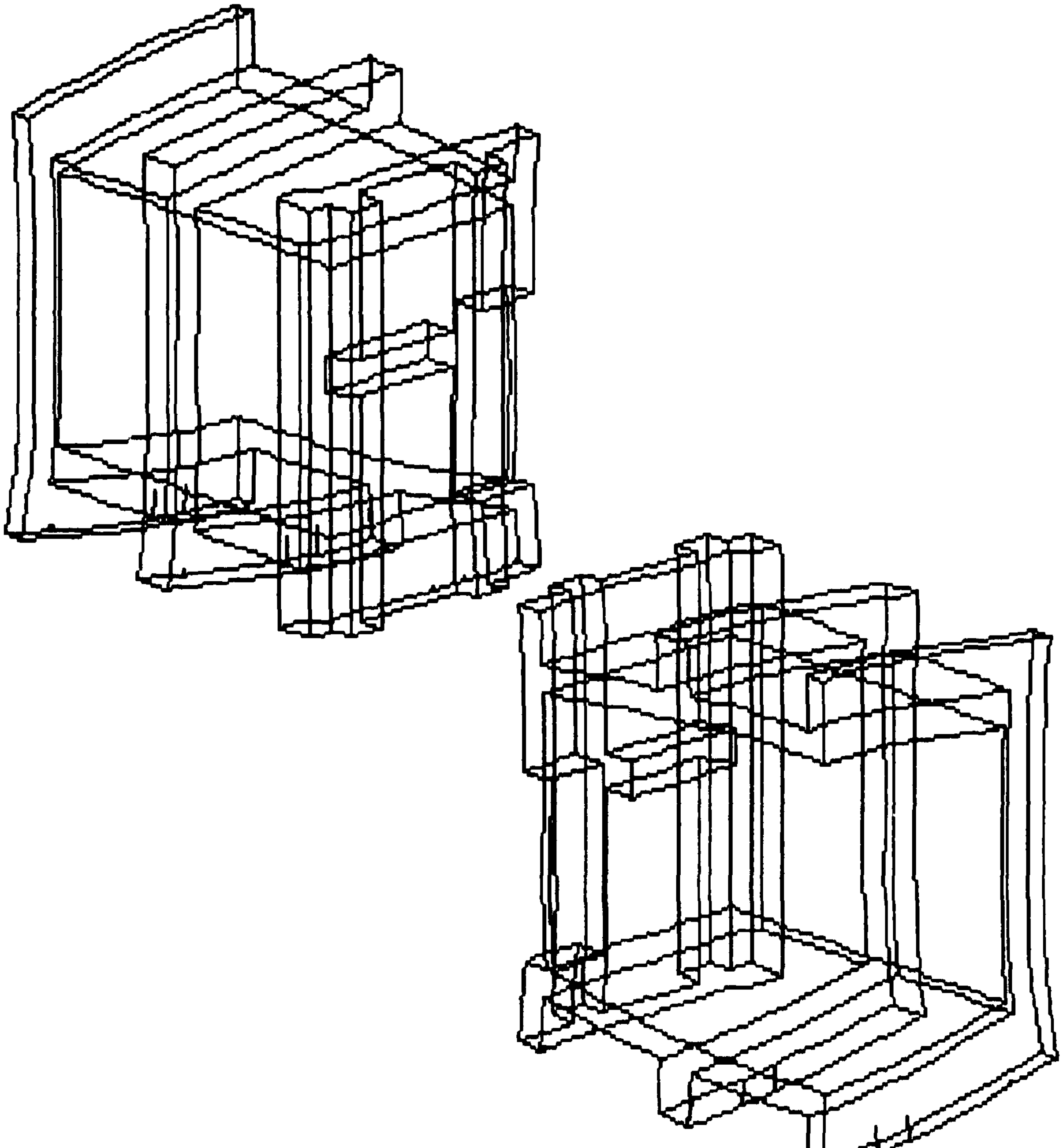


Figure 12 Displacements - Operational (6 ATA) Case

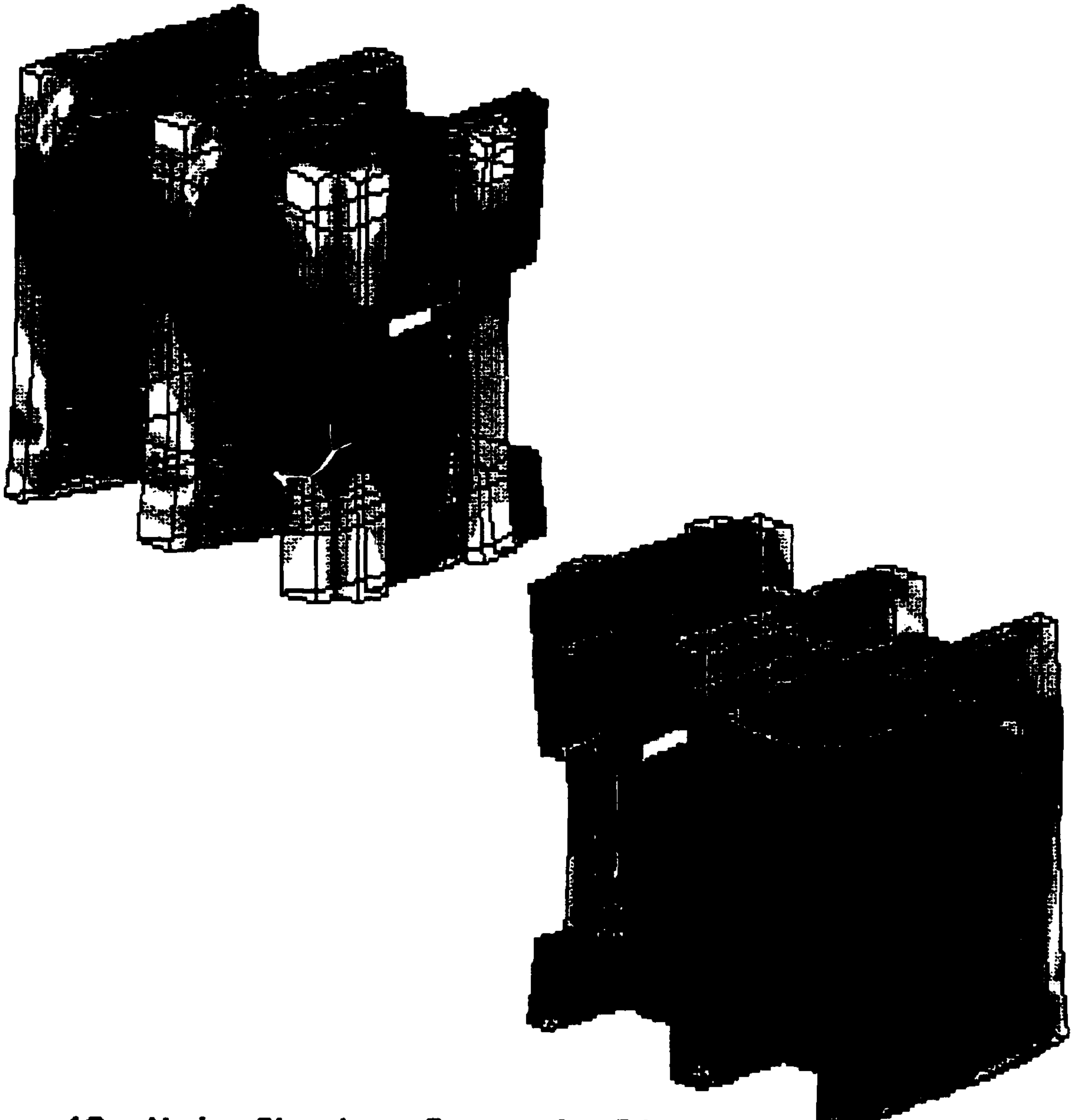


Figure 13 Main Chamber Concrete Stresses - PostTensioned Case

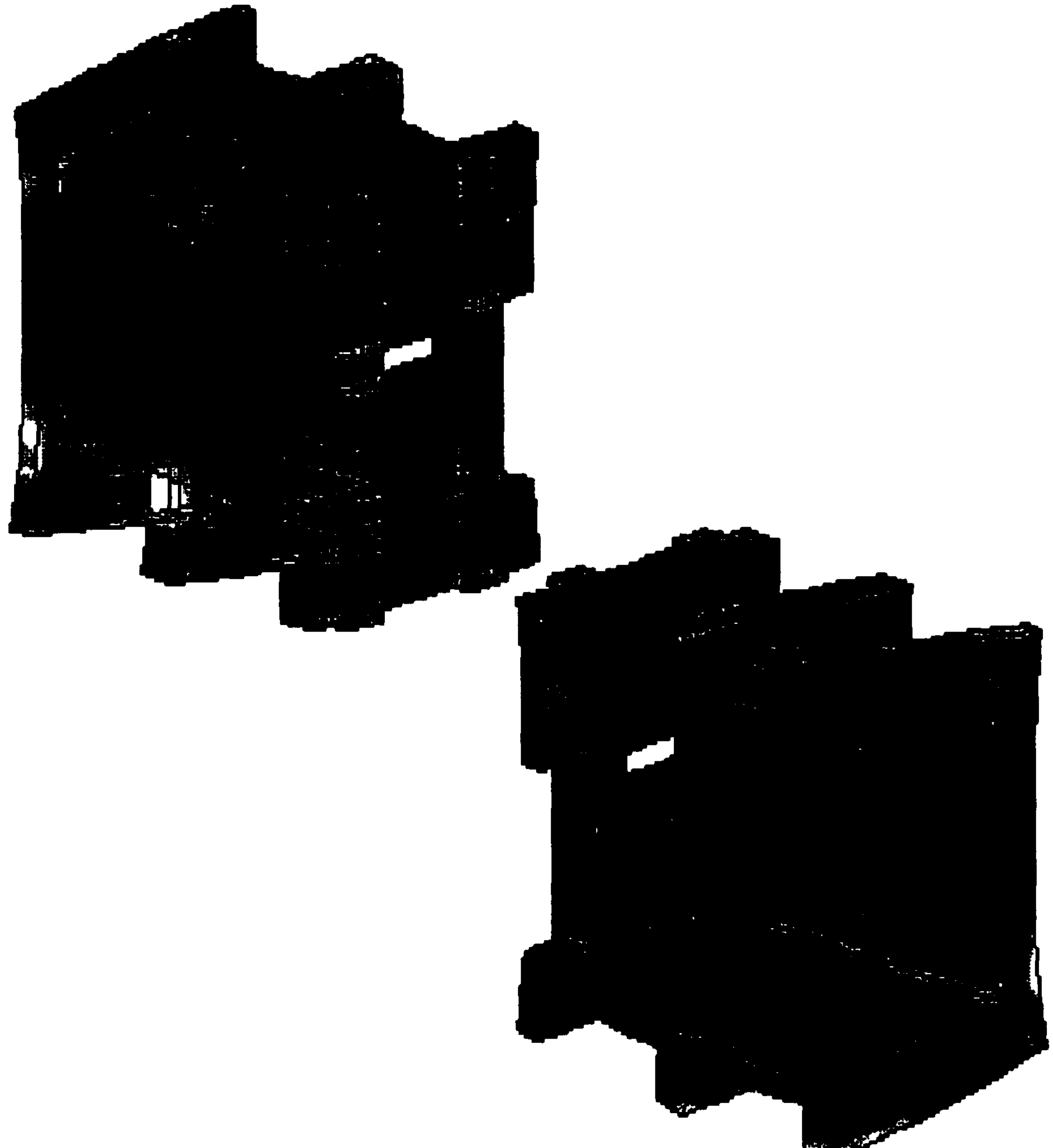


Figure 14 Main Chamber Concrete Stresses - Operational (6 ATA) Case

1. the general stress condition in the chamber,

2. regions of local stress concentration,

3. the distribution of load in and between the buttresses and walls, and

4. when compared to allowable values from the ACI or ASME Code, as a measure of design adequacy.

The ACI Code concrete strength allowables are given in Table 2 for three concrete strengths and two loading conditions. The operating condition membrane plus bending stress allowables for concrete are [0.45 * f'c] for compression and [6 * sqrt(f'c)] in tension. In local regions the tensile stress may be increased by a factor of 2. During post-tensioning, the ACI Code permits concrete compressive stress to be as high as [0.6 * f'c].

TABLE 2 - ALLOWABLE CONCRETE STRESSES

Concrete Strength	6,000 psi	12,000 psi	18,000 psi
Operating Compressive	2700 psi	5400 psi	8100 psi
Post-Tension Compressive	3600 psi	7200 psi	10800 psi
Average Tensile	465 psi	657 psi	805 psi
Local Tensile	930 psi	1314 psi	1610 psi
ACI Elastic Modulus	4,696 ksi	6,641 ksi	8,134 ksi

The contours displayed on Figure 15 through 18 represent the allowable concrete stresses in 6000 psi concrete. The green shades are for regions where the compressive stress does not exceed the operating compressive allowable of 2700 psi. The higher compressive limit permitted during post-tensioning is shown as light blue. Yellow regions have tensile stress that is less than the 465 psi tensile limit. Local tensile limits are indicated with red. Darker shades of blue show regions of compressive stress beyond the ACI Code limits.

Figure 15 shows that the compressive prestress is concentrated in the corners and in the ceiling beams. High compression is expected at the corners where vertical and horizontal tendons meet. The higher prestress in the ceiling beams was applied to counteract the large bending effect of internal pressure. The tensile stresses are shown to the lower right. The prestress in the ceiling beams causes a tensile stress to develop on the outside of the vertical side wall buttresses.

The application of internal pressure, Figure 16, increases the region of tensile stress on these buttresses. The internal pressure also produces tensile stress in the extreme fibers of the transverse ceiling and floor beams. The selection of preload in these members will require care to insure an acceptable stress level. It is noted again that the FEM model averaged the tendons across the concrete section and a more exact treatment that places tendons near the extreme fibres may produce lower tensile stress in the concrete.

The wall stresses, shown in Figures 17 and 18, are within ACI Code allowables. The only regions that show tension are around the door and at the inside corners. Local steel rebar reinforcement would be provided in these regions.

Tendon strains and stresses are illustrated in Figures 19 and 20. The ACI Code allowable for tendons during prestress is 85% of the tendon tensile strength. It is expected that tendon stress will diminish by about 20% as a result of creep and shrinkage in the concrete and relaxation in the tendons. For a 270 ksi tendon, the allowable stress during post-tensioning is 230 ksi. The tendon stresses do not exceed the Code allowables, however, an interpretation that tendon stresses are acceptable must be deferred to the final detailed design.

The FEA analysis confirms the feasibility of the proposed design for the main treatment chamber. A cost estimate can be prepared using the preliminary design sizes and material volumes. Additional analysis is needed to develop a detailed design.

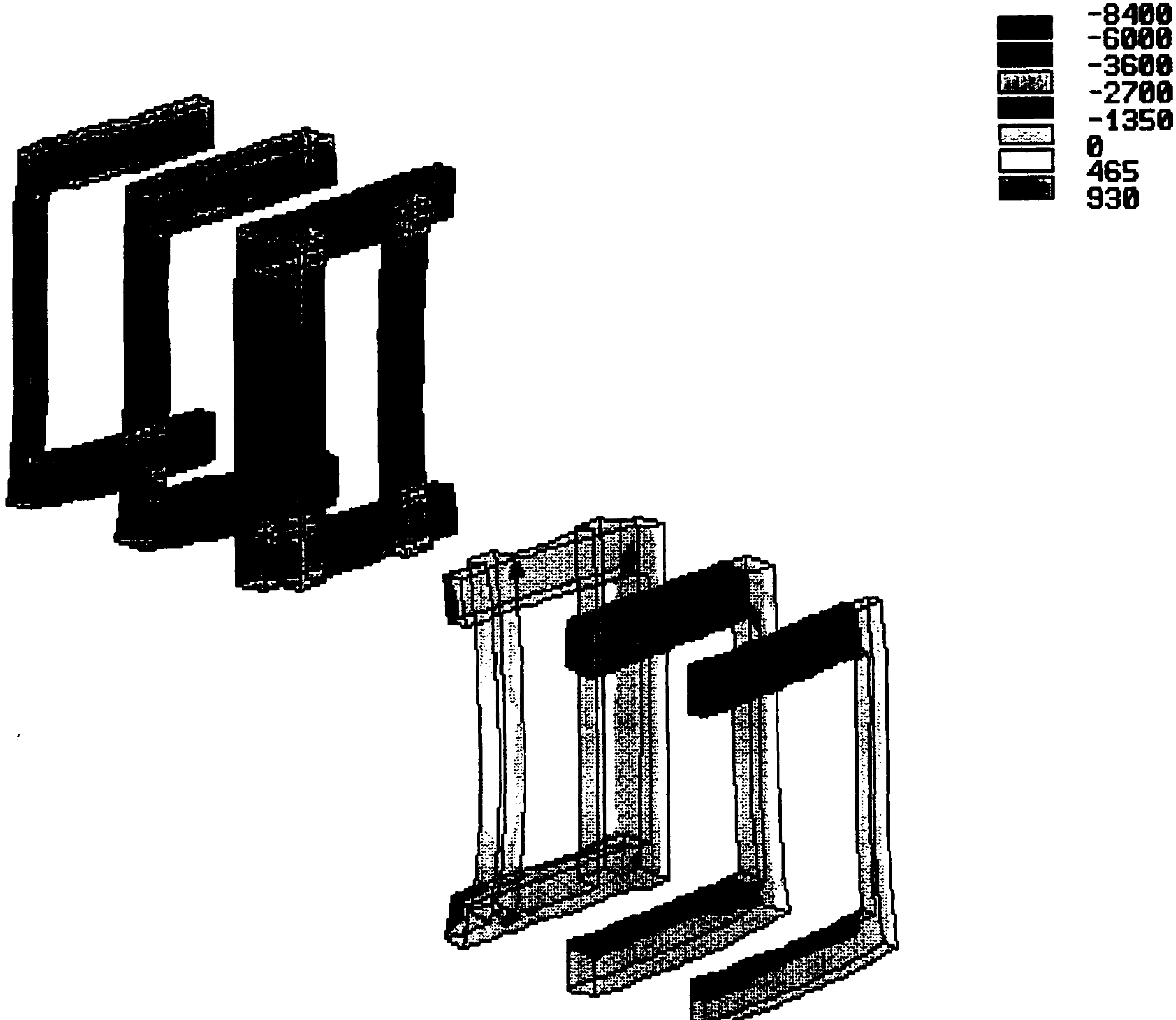


Figure 15 Buttress Stresses - PostTensioned Case

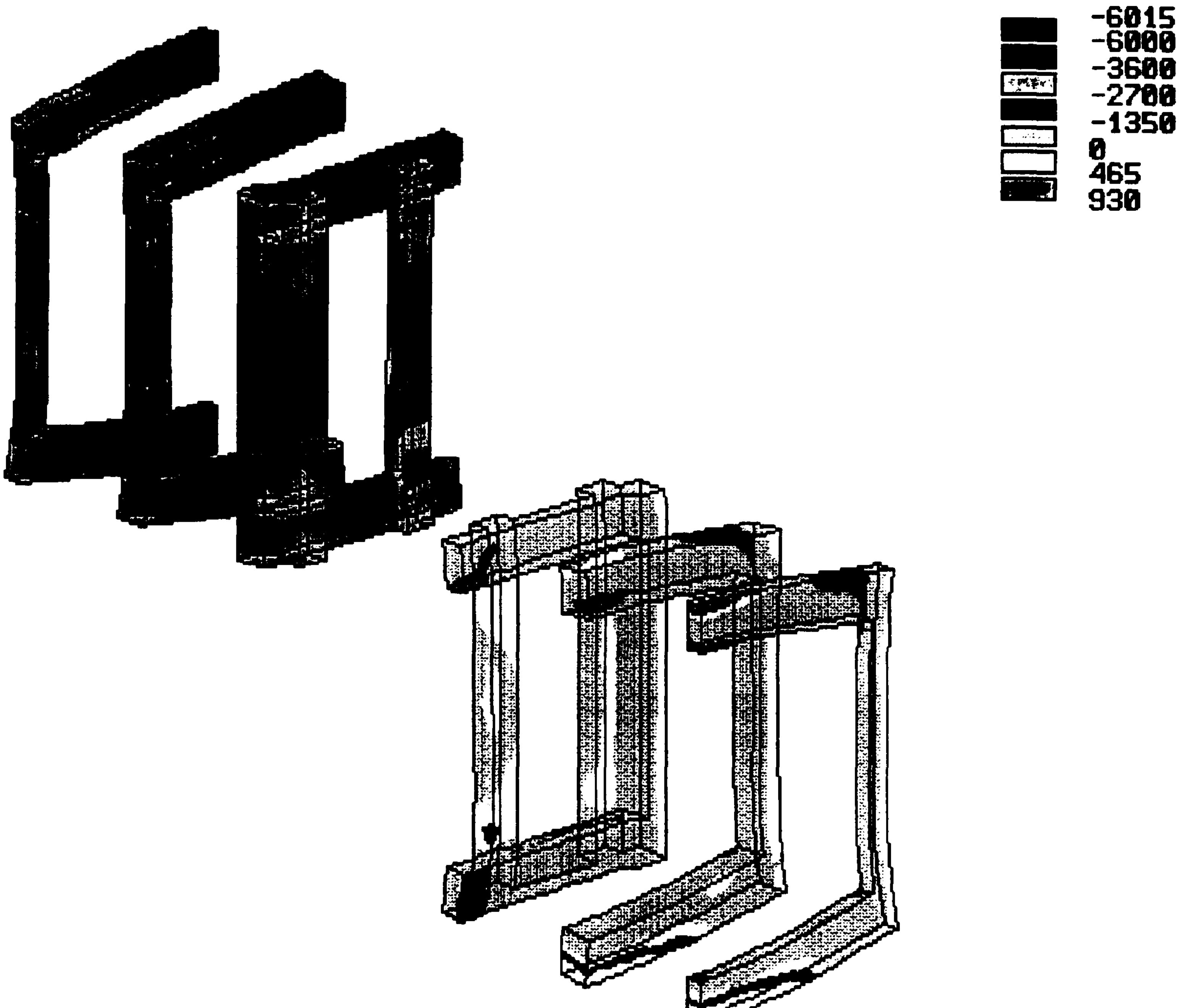


Figure 16 Buttress Stresses - Operational (6 ATA) Case

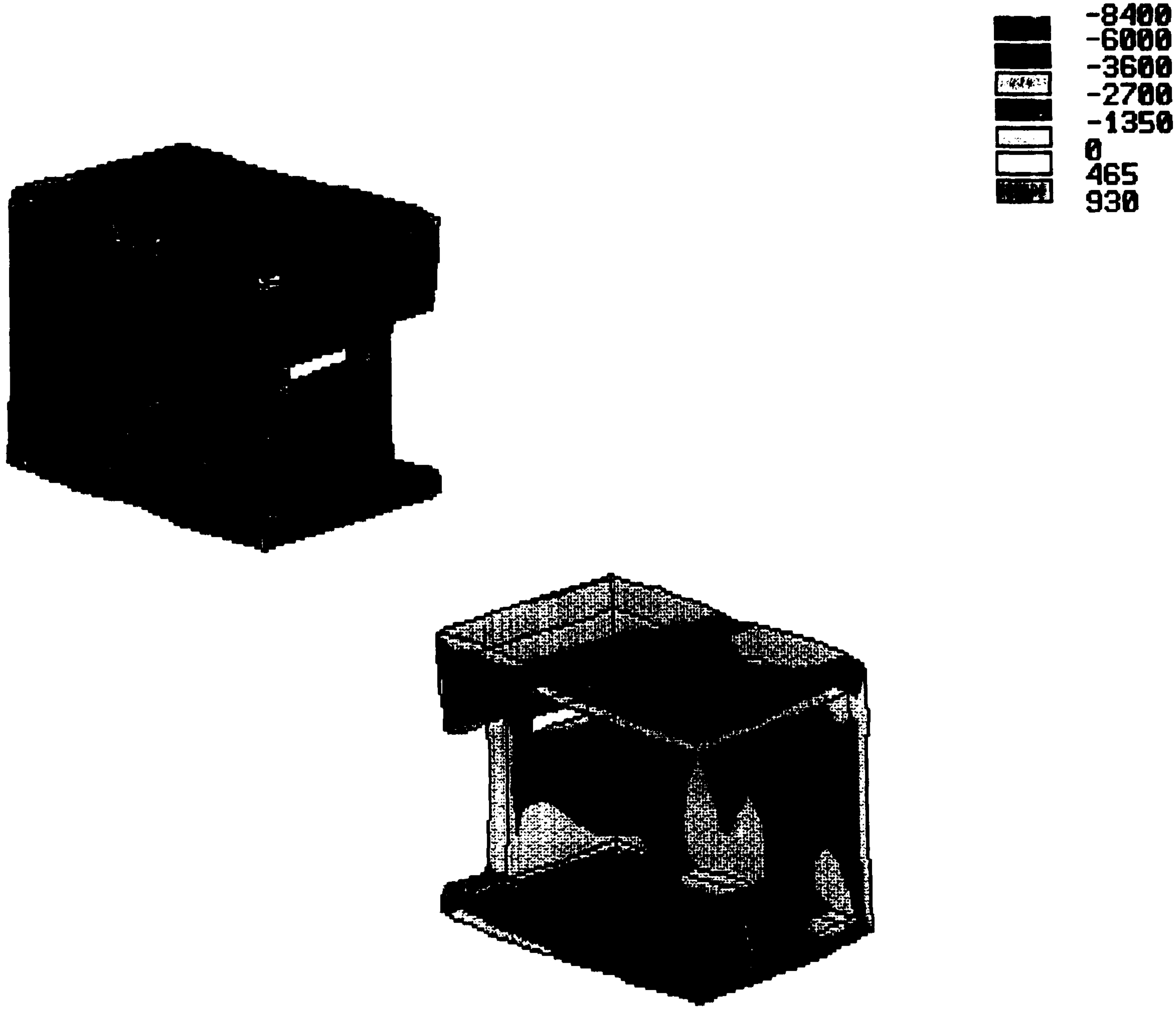


Figure 17 Wall Stresses - PostTensioned Case

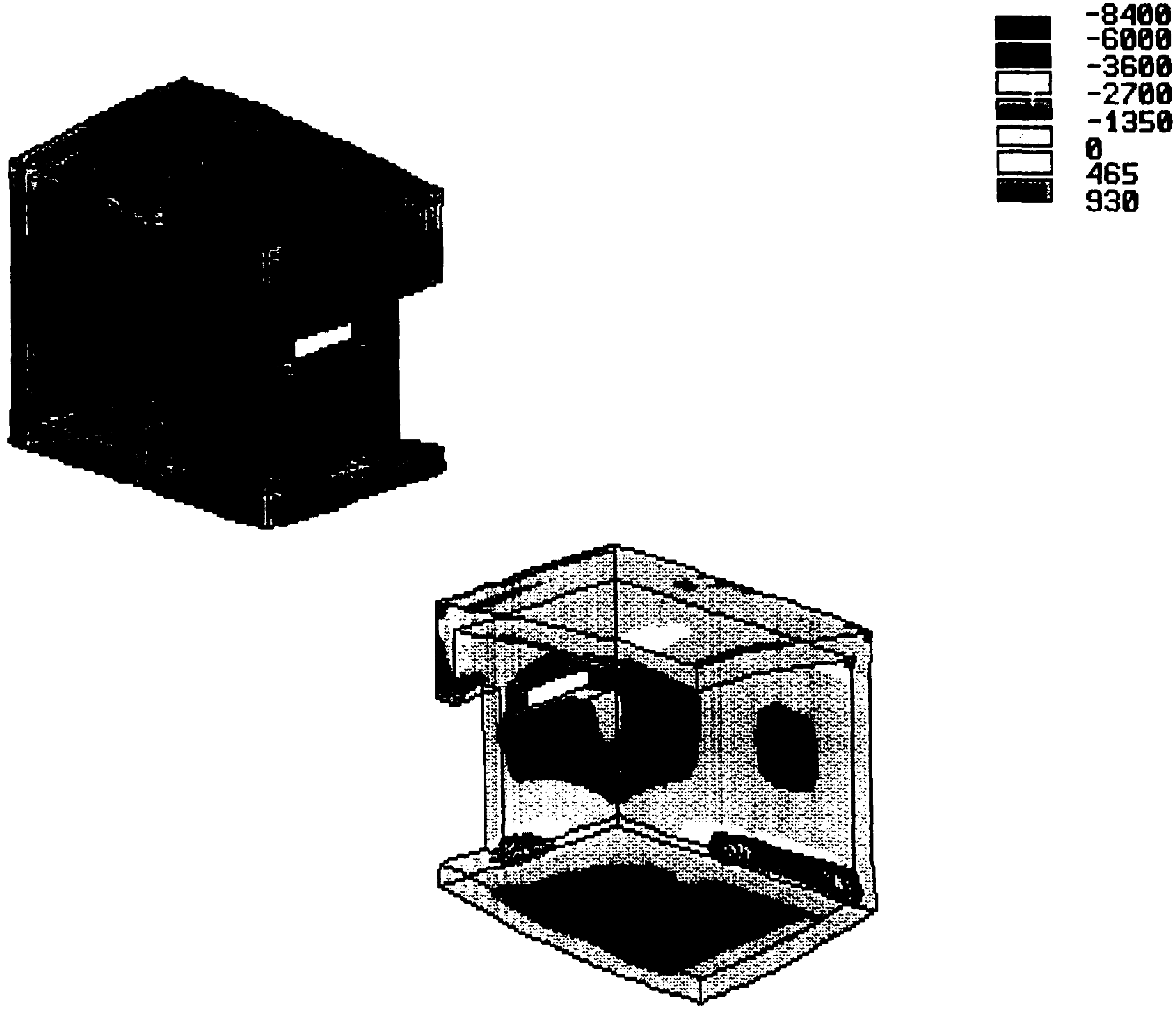


Figure 18 Wall Stresses - Operational (6 ATA) Case

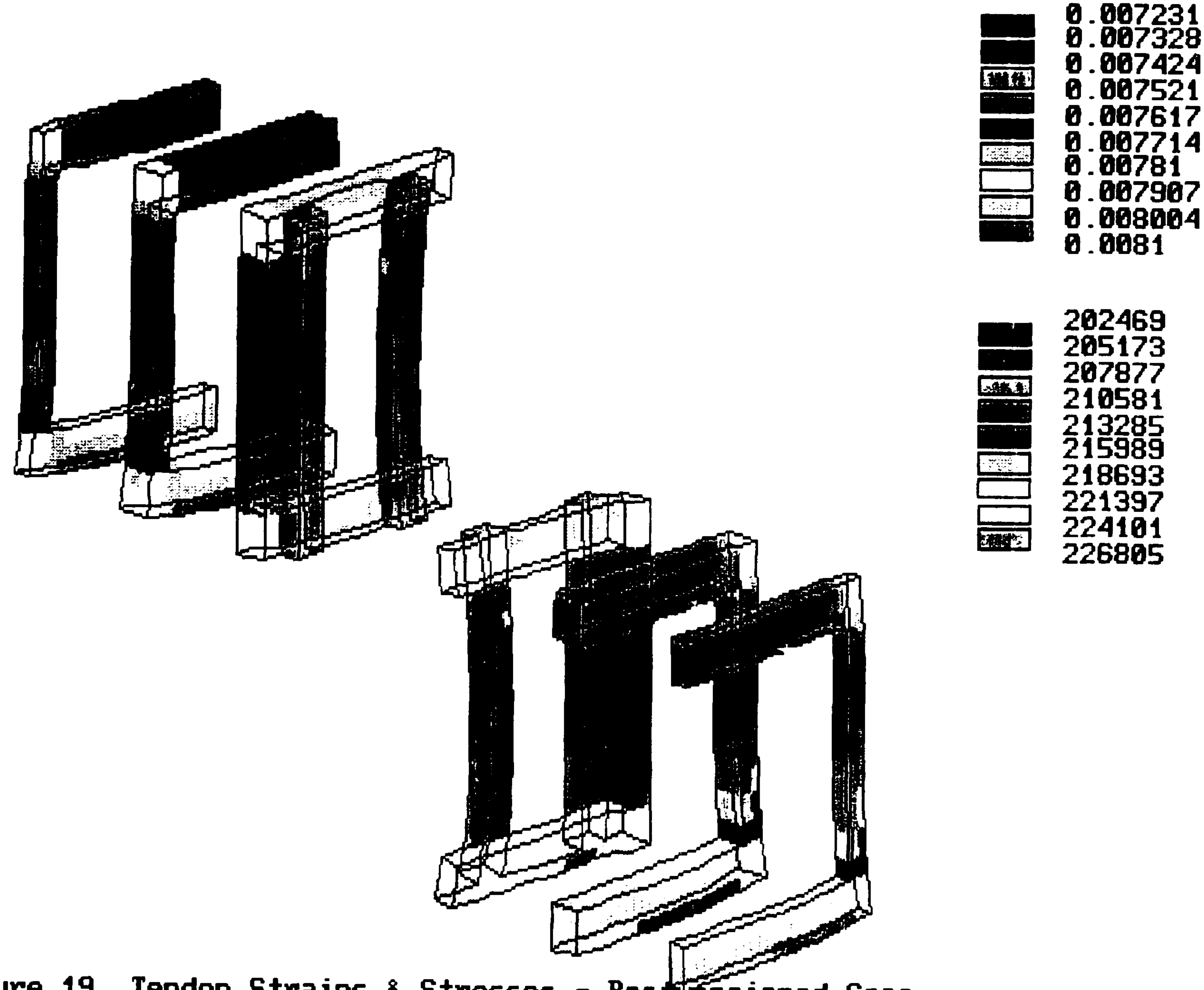


Figure 19 Tendon Strains & Stresses - Posttensioned Case

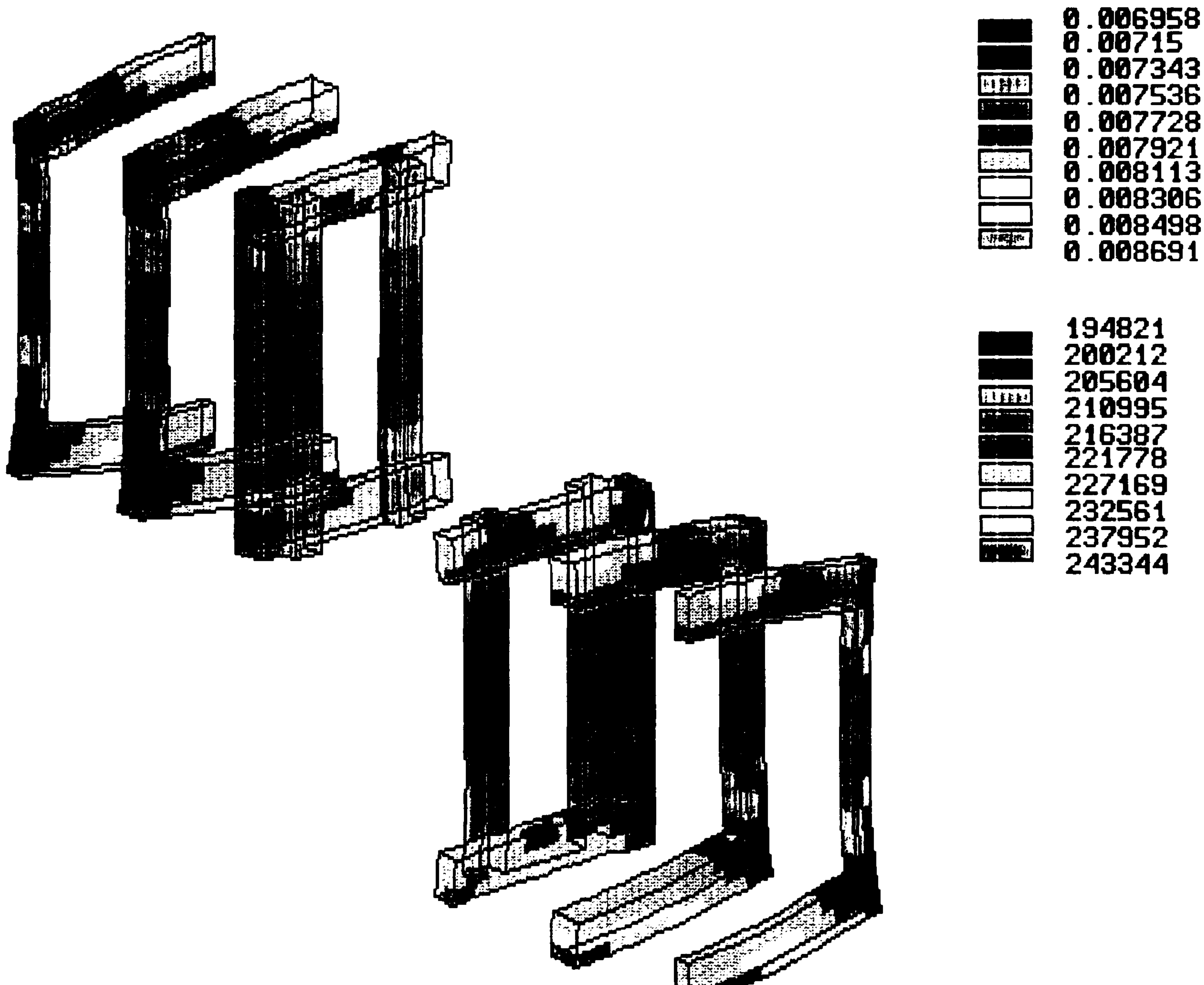


Figure 20 Tendon Strains & Stresses - Operational (6 ATA) Case

FINITE ELEMENT ANALYSIS OF SLOT WINDOW

An unconventional slot-shaped PVHO window is proposed. Windows in medical PVHO chambers are circular and made from acrylic plastic. The PVHO Code has rules for the design of flat circular or disk windows; however flat rectangular windows are not covered.

The circular window is not the ideal shape for a rectangular concrete room. The desirable shape is a long window located at eye height. A long window permits the observer to view the chamber by rotating rather than moving the head. Multiple circular windows must be placed side to side to achieve a panoramic view of the patients. Multiple windows in close proximity may pose structural design problems.

The proposed window for a rectangular concrete PVHO is rectangular with rounded ends. The window is 15" wide by 48" long with a clear viewing area of 12" wide by 45" long. The ends are semi circular. This slot window is not a PVHO Code approved design.

The PVHO rules require an extensive test program for new window designs. Five short term failure tests, 5 long term creep tests, and 2 fatigue tests must be performed. Currently there are no rules for windows to be designed by finite element analysis. The PVHO rules are based upon empirical test data. The conventional practice for design of acrylic windows accounts for the viscoelastic and creep effects in acrylic through a "Conversion Factor". The PVHO conversion factor varies with window shape, design pressure and operating temperature. Factors range from a low of 4 to a high of 25. The conversion factor is essentially a safety factor on tensile stress. Attempts to correlate the experimental data to analytical predictions have not been successful; however, there is a recognized need for a design analysis option to the expensive experimental program. One approach that develops a "pseudo-allowable" design stress is described.

Assuming that the conversion factor is a safety factor, then a design allowable stress can be found and this stress used for comparison to stresses found from a FEM analysis. Given the PVHO minimum tensile stress of 9000 psi and the conversion factor of 8 for a flat window at $<$ 100 degrees F, a pseudo-allowable stress for acrylic windows is 1,125 psi.

The thickness of the slot window will be confirmed with a FEM analysis, but a preliminary thickness must be specified. In addition to the structural consideration, window thickness should not exceed 4" thick. Acrylic sheet is available to 4" thickness and while thicker sections can be cast, quality control is more difficult and costs escalate. The initial window thickness is therefore 4".

The FEM model for the 4" thick slot window is shown in Figure 21. It consists of 936 three dimensional solid elements. A line support is assumed 1.5" from the edge running completely around the window. The resulting 12" wide by 45" length opening is loaded with a 6 ATA pressure. The bottom view on Figure 21 illustrates these conditions. Pressure is red and displacement constraints are blue.

The FEM results are shown in Figure 22. Von Mises effective stresses are displayed and referenced in the color key to the right. The maximum stress develops at the center of the window. The maximum stress of 694 psi is less than the pseudo-allowable of 1125 psi. While the FEM analysis predicts an acceptable slot window design, experimental confirmation in accordance with the PVHO rules is required.

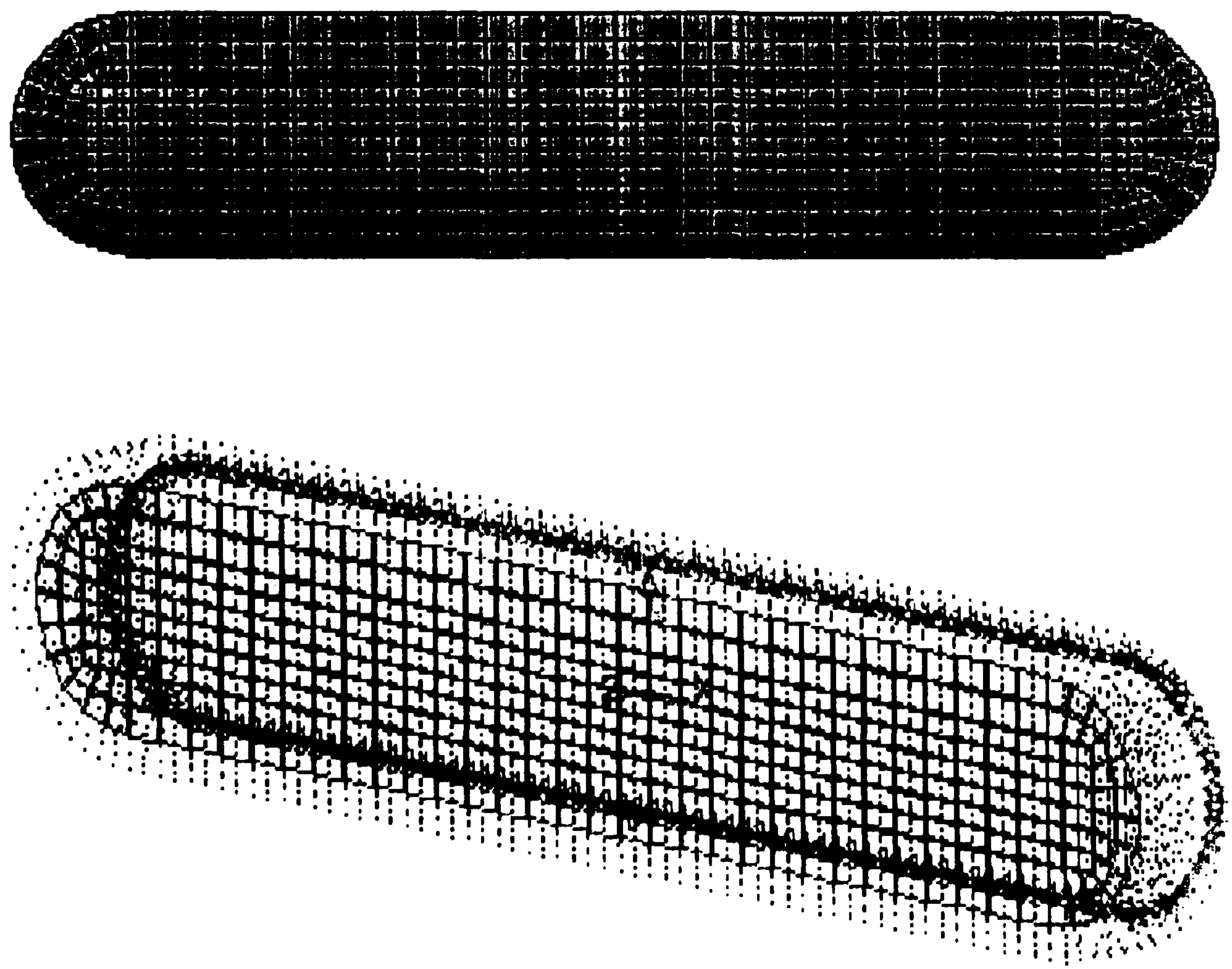


Figure 21 Slot Window (48" long - 12" view height - 4" thick)

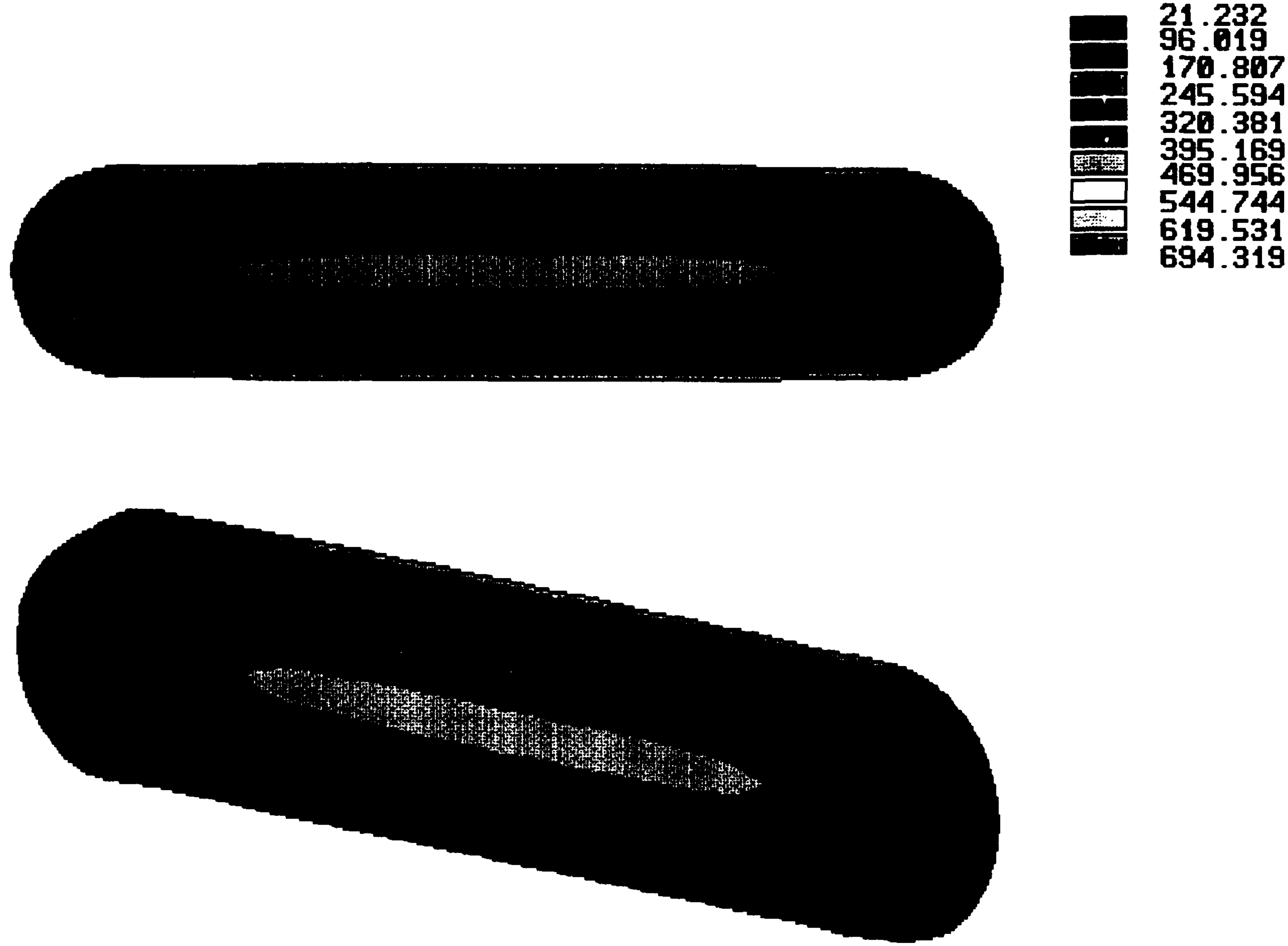


Figure 22 Slot Window Effective Stress

FINITE ELEMENT ANALYSIS OF RECTANGULAR DOOR

Rectangular doors are specified for most medical multiplace PVHOs. The door is sized to seal a rectangular opening of about 32" wide by 72" high. The doors also have a circular window located at eye level. A common practice is to specify the door thickness at twice the ASME Code design thickness so that the window opening requires no added reinforcing. This approach which is dictated by costs, yields very heavy doors.

Numerous FEM studies have shown that corner stresses in the mating door frame can be controlled by adding a corner radius of 3"-4". These studies have also revealed that the door makes contact along the edges except at the corners where it moves away from the frame.

The door desired for the concrete PVHO was larger than any specified for a PVHO. A 60" wide by 84" high opening would improve patient movement and was considered a necessity. The window in the door was specified at 24" clear opening.

The door was designed using the ASME rules for flat rectangular openings. The minimum thickness was calculated to be 2-3/4". If the door thickness were doubled to make the window opening self reinforcing, the door would weigh 5 tons. The door thickness is maintained at ASME Code limits and the window is reinforced locally.

The FEM model of the door is shown in Figure 23. The window, shown in purple is 4" thick. The 6" thick window reinforcing is shown red. A plate model consisting of 820 elements is loaded with 6 ATA pressure. The edges are restrained in the plane of the model except at the 6" radius corners.

Stresses are shown in Figure 24. The contours to the right are top for the door steel and bottom for the acrylic window. ASME Code allowable stress is 17,500 psi. The door meets this requirement. The maximum stress in the acrylic window is 519 psi, also well below the pseudo-allowable stress of 1125 psi.

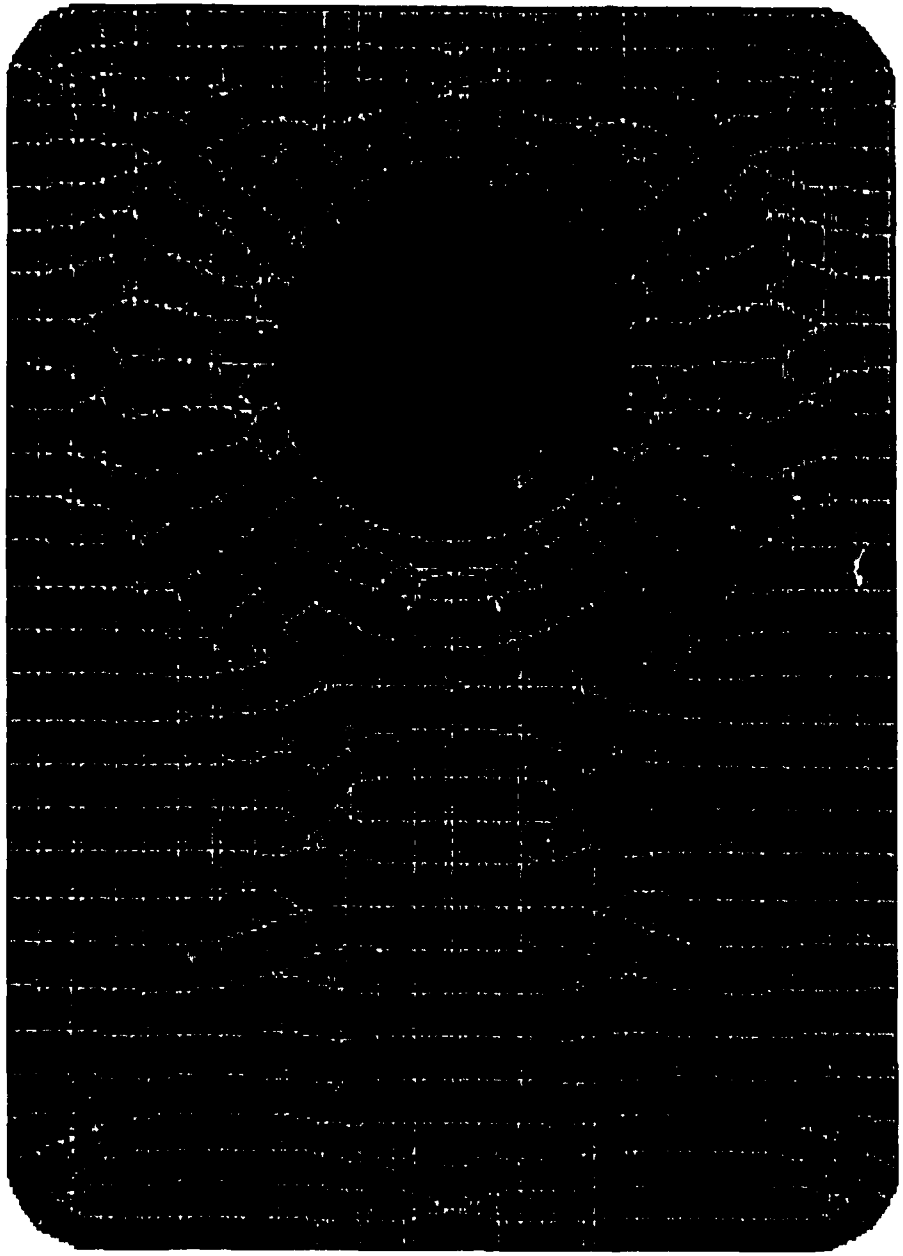


Figure 23 Rectangular Door (6 ft wide by 7 ft high with 24" window)

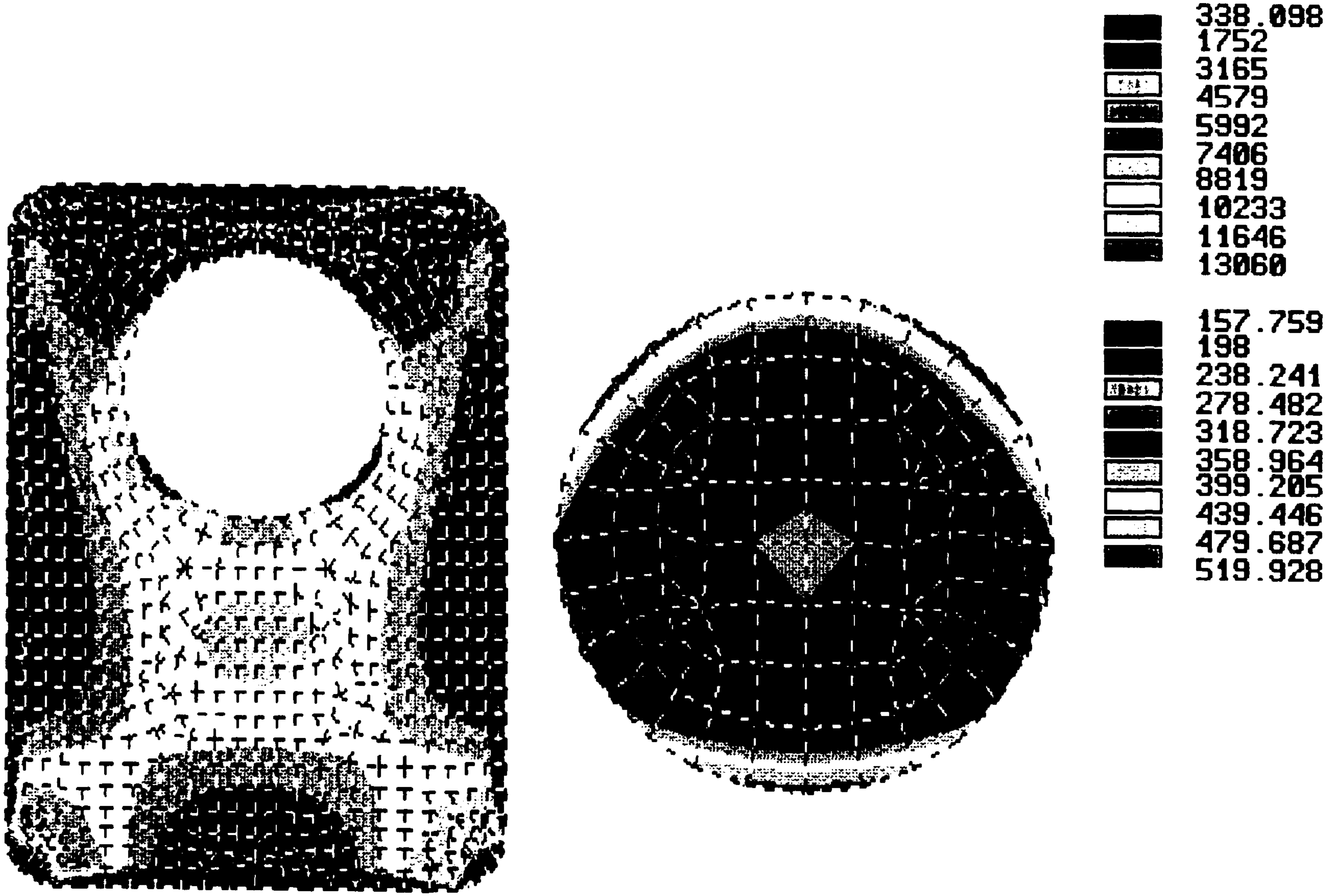


Figure 24 Rectangular Door and Window Stresses

COST

A prime objective of this study was to compare the cost of a concrete rectangular room to cost of a conventional steel PVHO. To compare concrete to steel, a base line concrete design was needed. A post-tensioned concrete room 27 foot long, 18 foot wide and 10 foot high was the base line chosen. This room configuration, shown in Figure 6, has been designed to the ACI Code and the design confirmed by finite element analysis.

The unit cost for conventional 6,000 psi post-tensioned concrete is $300 to $400/cu.yd. installed. Higher strength concrete is more costly. Relative concrete costs were reported in 1986 for a Chicago high rise. The costs are for concrete only.

Cost for: 6 ksi was $ 58.81 cu.yd. or $9.8 / cu.yd. / ksi, and

14 ksi was $145.33 cu.yd. or $10.4 / cu.yd. / ksi.

This data suggests that concrete cost is proportional to strength. In Seattle, high strength concrete cost 3 times conventional strength, but the high strength, 19,000 psi was about 3 times as strong as conventional concrete. Based upon these data, the cost of concrete is approximately proportional to strength.

High strength concrete costs more per cubic yard but the reduction in the size of members may be offsetting. In an attempt to uncover the cost sensitivity of higher strength concrete, a preliminary design of three different room geometries using three concrete strengths was done. The basic variable in room geometry was the spacing between buttresses. The base design used a 6-1/2 foot spacing. If one buttress was removed, the spacing would be increased to 8-1/2 foot. An intermediate spacing of 7-1/2 foot was also calculated as representative of longer rooms. Concrete strengths investigated were 6,000 psi, 12,000 psi and 18,000 psi. Concrete costs were assumed proportional to strength.

The summary of costs is given in Table 3. The details of the cost analysis are in Appendix A.

TABLE 3 CONCRETE RECTANGULAR PVHO COSTS

Span (ft)	6 ksi ($300/yd)	12 ksi ($600/yd)	18 ksi ($1200/yd)
6.5	$46,135	$80,683	$151,532
7.5	$45,402	$78,832	$147,588
8.5	$44,891	$77,615	$144,715

The cost data clearly indicate that the design is not sensitive to span length, but is strongly dependent on concrete strength. The higher the strength the greater the cost. Closer examination of the individual designs showed that the controlling factor was the allowable tensile strength of the concrete. Unfortunately the value of increased compressive strength is not fully appreciated in a tensile strength increase. The ACI Code gives credit for increases in tensile strength as the square root of compressive strength, not in proportion to compressive strength.

The least expensive alternative is the longer span in low strength concrete. However, the conclusion that the 8-1/2 foot span is best, needs further study. The cost sensitivity study was an exercise that assumed reinforcing requirements of the ACI Code could be accommodated in the beam sections used. The only design that received careful review was the 6-1/2 foot span of the proposed design. Since the cost differential between the different span widths is small and the details of the shorter span has been carefully checked, the 6-1/2 foot span is selected as the preferred design.

The selection of conventional strength concrete accrues side benefits. At lower strengths a large tolerance on mix design can be accommodated. The availability of competent local producers is increased. Also, the hospital contractor will have familiarity with placement problems.

The total estimated cost for rectangular concrete 6 ATA PVHO is $200,000. The main chamber will cost $50,000, eight windows at $6,000 each will add another $50,000, the doors (2) are estimated to cost $50,000 and $50,000 is included for other structural details. Note that the concrete room accounts for only 25% of the estimated cost.

The total structural cost for a three chamber complex is developed from the assumption that costs are proportional to length and that the chambers can be constructed in tandem, see Figure 3. A 45 foot total length is assumed for the three chamber complex. The structural cost for a PVHO rectangular room complex comparable in size and functionality to a steel CHF is $350,000.

The cost of large medical PVHO steel vessels is known. The vessel costs alone in the first USAF HBO at Wright Patterson, the WPCHF, was more than $1,350,000. The second PVHO at Travis AFB and the DGCHF vessels cost $1,600,000. The projected cost for the Portsmouth Naval Hospital PVHO chambers is also $1,600,000. For comparison, the current price for a commercial multiplace PVHO is about $10 per pound of steel.

The concrete CHF at an estimated cost of $350,000 compares favorably to steel at $1,600,000. Concrete is 22% the cost of steel. This is in the range of 70% cost savings found in other studies of concrete versus steel.

A number of potential cost risers exist, however. The concrete room will be first of a kind and start up problems need to be allowed for. The installation of the stainless steel lining and its use as a concrete form could pose difficulties, particularly with the floor.

A major expense will be the detailed design of the first rectangular concrete PVHO. The ACI ultimate strength method used in the feasibility study will probably require experimental or analytical confirmation. Experimental confirmation makes some sense considering the relatively low cost of a concrete PVHO. A more credible scenario would have the experimental program follow a detailed design study using finite element analysis and the elastic strength rules of ASME, Section III, Division 2. The ASME rules have been in existence for more than 15 years, but have been applied in relatively few instances. The cost of familiarization of civil structural designers to the ASME rules may increase the detailed design cost a significant amount. The detailed design of the first rectangular concrete PVHO could be as much as $150,000.

A counteracting factor is the potential to reuse this detailed design on successive PVHOs. The feasibility study showed that the room can be expanded to meet specific size requirements. If the width of the room is held constant, length can be varied without major design impact. Accordingly, a generic design for concrete PVHOs can be developed, thoroughly analyzed, possibly built and tested as a prototype and then applied to subsequent hospital installations. Amortization of design, development and testing costs across two or three facilities would make the cost comparison even more attractive. The experimental program leading to certification of the slot window will be costly. A prototype window is estimated to cost $25,000. Subsequent windows will cost less, but the experimental effort could be as much as $100,000.

The large door may prove more costly than estimated. It too is a new door design. The structural design is straight forward and is based on considerable experience and success. FEM is well suited for design optimization and a cost tradeoff of conventional uniform thickness versus local reinforcement should be made. The mechanical design of the door is less obvious and may increase costs. A sliding door appears a logical choice with support provided from the floor or hung from the ceiling. A sliding door gives excellent space utilization but will require a mechanical assist. Sealing of the door may prove difficult.

The QA awareness of hospital contractor may lead to increased cost. If the contractor sees QA as a risk, due to lack of familiarity, price will rise. An associated QA cost is the effort required for first of the kind Code approval. The first RPC/PVHO (Rectangular Post-tensioned Concrete Pressure Vessel for Human Occupancy) will require ASME PVHO, ACI, the local jurisdiction building inspectors, and possibly the ASME Boiler and Pressure Vessel Code Nuclear Certification groups concurrence.

CODE COMPLIANCE

The primary group responsible for codification of rules for design certification of medical HBO systems is the ASME Committee for Pressure Vessels for Human Occupancy (PVHO). The PVHO rules, (ref. 2), were developed as an industry consensus standard. The rules have been adopted by the US Coast Guard, the US Navy and the US Air Force as minimum requirements for the design, fabrication and testing of PVHO chambers. PVHO-1 is also recognized by the National Board of Boiler and Pressure Vessel Inspectors and local, state and international regulatory groups. Users of all recent commercial PVHO vessels invoke PVHO-1 in their purchase specifications.

Industry acceptance of prestressed concrete for PVHO rectangular chambers will follow only after the rules of PVHO-1 are revised to include concrete as an approved material of construction. Rule changes are made to PVHO-1 through either of two techniques. If an existing safety standard covers all or part of the special requirements of PVHO, the standard can be adopted by reference. This is the method used to include rules of the ASME Boiler and Pressure Vessel Code, Section VIII, and ANSI B31.1 for piping. If the special needs of PVHO have not been developed by other standards, then a development effort is begun within the PVHO Committee. This latter approach led to the acrylic window rules now widely referenced throughout the world, and the special provisions for design of spheres exposed to external pressure.

Two industry standards organizations are involved with safety standards for prestressed concrete construction; the American Concrete Institute (ACI), and the ASME Section III, Division 2 subcommittee. The ACI develops rules that are adopted as the Uniform Building Code and are applied to buildings, bridges and other prestressed concrete civil engineering structures. The ACI Code is widely known and is familiar to hospital building contractors. Unfortunately it is not specifically developed for pressure vessels and as a commercial code it does not have a rigorous QA plan to guarantee quality.

The ASME Code is much better suited for pressure vessels constructed of prestressed concrete than the ACI building code. The ASME and the ACI formed a joint working group to develop rules for concrete nuclear pressure vessels in the early 1970's. That group continues today, albeit at a low level of activity. The ASME Section III, Division 2 (ref. 4) offers rules that are directed specifically to post-tensioned concrete pressure vessels. The rules were written for nuclear reactor vessels and accordingly insure a high degree of safety. While increased safety is desirable, it results in increased design analysis, paperwork and cost. In spite of these potential difficulties, the application of the ASME rules is the most direct means for adoption of prestressed concrete into the PVHO-1.

The ASME rules for concrete nuclear reactor vessels distinguish two categories; for reactor vessels, (Section CB) and for containment, (Section CC). The reactor vessels are exposed to high internal operating pressures, high temperatures and intense radiation. The containment vessels surround the reactor vessels and provide backup low pressure resistance in the event the reactor fails. The containment vessels are buildings and are designed using variants to the ACI Code requirements. The containment vessel is designed using the ACI concepts of load factors and ultimate strength.

The reactor vessels are designed using the elastic response method. The reactor vessel is required to operate in the elastic portion of the stress-strain curve. Furthermore, the vessel must demonstrate a "gradual, observable and predictable response to overload". The ultimate capacity of the concrete pressure vessel must be at least twice the maximum pressure. The finite element method is used to validate the reactor vessel design.

The reactor design method is consistent with current practice for PVHOs. The design methods are well established and familiar to the PVHO Committee and the ASME standards organization. Acceptance of this technology is therefore expected. Accordingly, the ASME Section III, Division 2, Subsection CB rules are recommended for adoption by PVHO-1 and will in turn become the basis for acceptance of rectangular post-tensioned concrete pressure vessels for medical HBO therapy.

CONCLUSIONS

1. Post-tensioned concrete for large multiplace PVHO's is economical and costs about 1/4 that of an equivalent steel chamber. Moderate strength concrete of 6,000 psi compressive strength is the optimum and higher strength concrete up to 18,000 psi offers little reduction in member size. Rectangular concrete vessel design is controlled by the allowable tensile strength of concrete. Concrete cost is proportional to strength.

2. A rectangular room configuration is practical for concrete PVHOs. Rectangular rooms can be readily expanded to larger sizes. The proposed design is not sensitive to length. Intermediate walls permit segmenting a large rectangular pressure vessel into multiple rooms.

3. Slot windows can be designed with stresses that are low enough to gain PVHO acceptance. Experimental studies will be needed to confirm the slot window design.

4. Large rectangular doors are feasible and adapt well to rectangular rooms. A door five foot wide and seven foot high poses no special structural problems. Mechanical problems with actuation and sealing need careful attention during final detailed design.

5. Incorporation of the ASME Boiler and Pressure Vessel Code, Section III, Division 2, Subsection CB rules into PVHO-1 will provide a sound technical basis for post-tensioned concrete as a construction material for rectangular HBO therapy chambers.

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APPENDIX A. DETAILED COST BREAKOUT

RECTANGULAR CONCRETE PVHO COST ANALYSIS for 6,000 PSI CONCRETE

6.5 ft Span - 6000 psi

Total Cost $46,135

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			34519		$3,249	
Concrete	1491	22	32802	$0.0741	$2,430	75%
Tendons			312	$1.5000	$468	14%
Rebars			1405	$0.2500	$351	11%
Roof Beam			31721		$3,019	
Concrete	1366	22	30052	$0.0741	$2,226	74%
Tendons			300	$1.5000	$450	15%
Rebars			1369	$0.2500	$342	11%
Side Beam			13454		$1,175	
Concrete	1291	10	12910	$0.0741	$956	81%
Tendons			66	$1.5000	$99	8%
Rebars			478	$0.2500	$119	10%

7.5 ft Span - 6000 psi

Total Cost $45,402

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			38931		$3,712	
Concrete	1675	22	36850	$0.0741	$2,730	74%
Tendons			370	$1.5000	$554	15%
Rebars			1712	$0.2500	$428	12%
Roof Beam			35673		$3,452	
Concrete	1528	22	33616	$0.0741	$2,490	72%
Tendons			358	$1.5000	$537	16%
Rebars			1699	$0.2500	$425	12%
Side Beam			15407		$1,358	
Concrete	1475	10	14750	$0.0741	$1,093	80%
Tendons			81	$1.5000	$121	9%
Rebars			576	$0.2500	$144	11%

8.5 ft Span - 6000 psi

Total Cost $44,891

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			43039		$4,153	
Concrete	1845	22	40590	$0.0741	$3,007	72%
Tendons			427	$1.5000	$641	15%
Rebars			2021	$0.2500	$505	12%
Roof Beam			39239		$3,851	
Concrete	1674	22	36828	$0.0741	$2,728	71%
Tendons			416	$1.5000	$624	16%
Rebars			1995	$0.2500	$499	13%
Side Beam			17204		$1,526	
Concrete	1645	10	16450	$0.0741	$1,219	80%
Tendons			96	$1.5000	$143	9%
Rebars			658	$0.2500	$164	11%

RECTANGULAR CONCRETE PVHO COST ANALYSIS for 12,000 PSI CONCRETE

6.5 ft Span - 12000 psi

Total Cost $80,683

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			34316		$5,599	
Concrete	1491	22	32802	$0.1481	$4,860	87%
Tendons			289	$1.5000	$433	8%
Rebars			1225	$0.2500	$306	5%
Roof Beam			31519		$5,165	
Concrete	1366	22	30052	$0.1481	$4,452	86%
Tendons			277	$1.5000	$416	8%
Rebars			1190	$0.2500	$298	6%
Side Beam			13417		$2,113	
Concrete	1291	10	12910	$0.1481	$1,913	91%
Tendons			59	$1.5000	$88	4%
Rebars			449	$0.2500	$112	5%

7.5 ft Span - 12000 psi

Total Cost $78,832

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			38756		$6,369	
Concrete	1675	22	36850	$0.1481	$5,459	86%
Tendons			347	$1.5000	$520	8%
Rebars			1560	$0.2500	$390	6%
Roof Beam			35467		$5,862	
Concrete	1528	22	33616	$0.1481	$4,980	85%
Tendons			335	$1.5000	$502	9%
Rebars			1516	$0.2500	$379	6%
Side Beam			15356		$2,419	
Concrete	1475	10	14750	$0.1481	$2,185	90%
Tendons			66	$1.5000	$99	4%
Rebars			540	$0.2500	$135	6%

8.5 ft Span - 12000 psi

Total Cost $77,615

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			42834		$7,079	
Concrete	1845	22	40590	$0.1481	$6,013	85%
Tendons			404	$1.5000	$606	9%
Rebars			1839	$0.2500	$460	6%
Roof Beam			390[illegible]6		$6,501	
Concrete	1674	22	36828	$0.1481	$5,456	84%
Tendons			393	$1.5000	$589	9%
Rebars			1826	$0.2500	$456	7%
Side Beam			17157		$2,715	
Concrete	1645	10	16450	$0.1481	$2,437	90%
Tendons			81	$1.5000	$121	4%
Rebars			626	$0.2500	$157	6%

RECTANGULAR CONCRETE PVHO COST ANALYSIS for 18,000 PSI CONCRETE

6.5 ft Span - 18,000 psi

Total Cost $151,532

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			34444		$10,476	
Concrete	1491	22	32802	$0.2963	$9,719	93%
Tendons			277	$1.5000	$416	4%
Rebars			1364	$0.2500	$341	3%
Roof Beam			31658		$9,638	
Concrete	1366	22	30052	$0.2963	$8,904	92%
Tendons			266	$1.5000	$398	4%
Rebars			1340	$0.2500	$335	3%
Side Beam			13383		$3,999	
Concrete	1291	10	12910	$0.2963	$3,825	96%
Tendons			44	$1.5000	$66	2%
Rebars			429	$0.2500	$107	3%

7.5 ft Span - 18000 psi

Total Cost $147,588

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			38862		$11,840	
Concrete	1675	22	36850	$0.2963	$10,919	92%
Tendons			335	$1.5000	$502	4%
Rebars			1677	$0.2500	$419	4%
Roof Beam			35600		$10,860	
Concrete	1528	22	33616	$0.2963	$9,960	92%
Tendons			323	$1.5000	$485	4%
Rebars			1660	$0.2500	$415	4%
Side Beam			15326		$4,588	
Concrete	1475	10	14750	$0.2963	$4,370	95%
Tendons			59	$1.5000	$88	2%
Rebars			518	$0.2500	$129	3%

8.5 ft Span - 18000 psi

Total Cost $144,715

	lbs/ft	feet	Total weight	Cost/#	Total $	$ %
Floor Beam			42975		$13,114	
Concrete	1845	22	40590	$0.2963	$12,027	92%
Tendons			393	$1.5000	$589	4%
Rebars			1992	$0.2500	$498	4%
Roof Beam			39165		$11,958	
Concrete	1674	22	36828	$0.2963	$10,912	91%
Tendons			370	$1.5000	$554	5%
Rebars			1967	$0.2500	$492	4%
Side Beam			17131		$5,136	
Concrete	1645	10	16450	$0.2963	$4,874	95%
Tendons			74	$1.5000	$110	2%
Rebars			607	$0.2500	$152	3%

* U. S. GOVERNMENT PRINTING OFFICE: 1990--761-051/20111